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THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM

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USAF

The U.S. Air Force is concerned about the use of toxic processing at the Air Logistics Centers (ALCs). To reduce hazardous waste generation from cadmium electroplating, McDonnell Aircraft Division (MCAIR) of McDonnell Douglas, through EG&G Idaho, was requested to determine the feasibility of substituting ion vapor deposition (IVD) of aluminum, across the board, for cadmium electroplating processes. The IVD aluminum coating and process does not generate hazardous wastes. The current phase of this contract required technical, environmental, and economical comparisons between IVD of aluminum and cadmium electroplating. This report provides that information. Recommended research and development to be conducted in Phase II of the contract is also included. This document is the final report for Phase I of the project.

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EXECUTIVE SUMMARY

During the period of 1 February 1988 to 31 January 1989, McDonnell Aircraft Company (MCAIR) completed Phase I of a three-phase program to demonstrate that Ion Vapor Deposited (IVD) aluminum coating can replace toxic cadmium processing at the Air Logistics Centers (ALCs). The thrust of the program is to reduce hazardous waste production. Research and development considered necessary for an across-the-board replacement of cadmium will be conducted during Phase II of the program. Procurement of an IVD aluminum coater will be supported during Phase II. The coater will be installed at an ALC site for the demonstration of the IVD aluminum process during Phase III of the program.

A compilation of data comparing the IVD aluminum process to the various cadmium processes has been assembled into a data base handbook. This handbook provides the designer or process engineer with a technical data source when considering a substitute for cadmium. It also includes a review of aircraft parts now processed with cadmium at the five ALCs to identify parts for which IVD aluminum can immediately replace cadmium without concern and identify parts which exhibit "areas of concern." Research and development recommendations are made for supplemental processing to be used with IVD aluminum to enable adequate replacement of cadmium processing for parts exhibiting "areas of concern." Processing costs and environmental impact comparisons are made between IVD aluminum and cadmium. IVD aluminum processing was generally less expensive than cadmium, and the IVD aluminum process is nonpolluting. MCAIR and the Oklahoma City ALC coated "typical" ALC parts with IVD aluminum that are now processed with cadmium. These parts passed and exceeded the military specification corrosion resistance requirements. The generic nature of IVD aluminum was further demonstrated by testing coated panels and comparing results to the compiled data book. Phase I verifies that IVD aluminum can be substituted for cadmium without concern for most applications. For those applications where the substitution is not straightforward or where other technical issues must be considered, the reader is alerted and specific research programs are recommended.

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PREFACE

This report was prepared by McDonnell Aircraft Company (MCAIR), McDonnell Douglas Corporation, St. Louis, Missouri, as part of Phase I of Contract C87-101602, "Demonstration of Ion Vapor Deposition Aluminum Coatings." The program was conducted by the Material and Process Development Department at MCAIR, St. Louis. The program was administered by EG&G, Idaho for the Air Force Engineering and Services Center (AFESC). Mr. C.J. Carpenter (AFESC) was the Government technical and administrative program manager. This report summarizes work accomplished between 1 February 1988 and 31 January 1989.

This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical publication has been reviewed and is approved for publication.

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SECTION 1

INTRODUCTION

A. OBJECTIVE

The objective of this report is to verify the applicability of ion-vapor-deposited (IVD) aluminum as a replacement for cadmium processing at the Air Force Air Logistics Centers (ALCs). Whereas cadmium has been widely used as a corrosion-resistant finish on steel, the substitution with IVD aluminum provides acceptable or improved performance in virtually all applications. More importantly, the substitution will make a major contribution to reducing hazardous waste production and its associated adverse effect on the environment.

B. BACKGROUND

The IVD aluminum coating is applied in production coating equipment called Ivadizers®. The basic equipment consists of a steel chamber, a pumping system, a parts holder, an evaporation source, and a high-voltage power supply. A schematic of an IVD coater is shown in Figure 1. The IVD

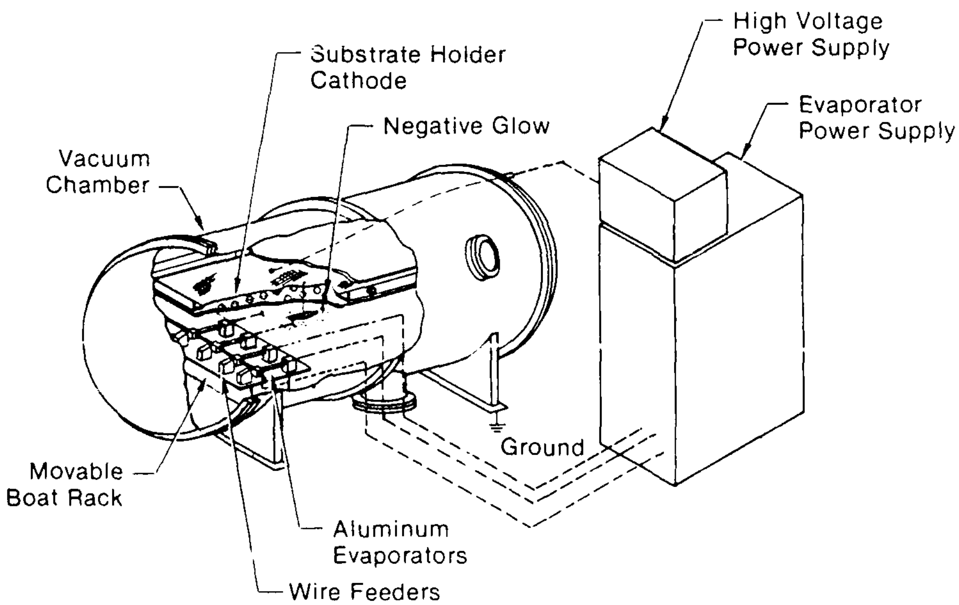


Figure 1. Schematic of an Ion Vapor Deposition System.

processing sequence consists of pumping the vacuum chamber down to about 10^{-4} Torr. The chamber is then backfilled with argon gas to about 10 microns, and a high negative potential is applied between the parts being coated and the evaporation source. The argon gas becomes ionized and creates a glow discharge around the parts. The positively charged gas ions bombard the negatively charged surface of the parts and perform a final cleaning, which contributes to good coating adhesion.

Following glow discharge cleaning, aluminum wire is evaporated by being continuously fed into resistance-heated crucibles. As the aluminum vapor passes through the glow discharge, a portion of it becomes ionized. This, in addition to collision with the ionized argon gas, accelerates the aluminum vapor toward the part surface, resulting in excellent coating adhesion and uniformity.

Both the aluminum coating and the IVD process are environmentally clean. Cadmium, on the other hand, is a heavy metal and is toxic to humans. Once it escapes into the environment, it can find its way into the water supply or food chain. Also, with electroplated cadmium processing, there are additional hazards associated with cyanide products in the plating bath. On the economic side, a suitable replacement can both reduce life-cycle costs and provide an immediate return on investment by eliminating those processing costs associated with hazardous waste collection, storage, and disposal.

There are inherent advantages to the substitution of IVD aluminum for cadmium, in addition to hazardous waste reduction. IVD aluminum outperforms cadmium in preventing corrosion in acidic environments and actual service tests. Also, aluminum coatings can be used at temperatures up to 950°F, whereas cadmium is limited to 450°F. IVD aluminum coatings can be applied to high-strength steel without fear of hydrogen embrittlement. Aluminum coatings can be used in contact with titanium without causing solid metal embrittlement, and they can also be used in contact with fuels; cadmium is prohibited for these applications. Additionally, IVD aluminum can be used in space applications, whereas cadmium is limited because of sublimation.

The coating requirements for IVD aluminum are specified in MIL-C-83488, the tri-service specification for pure aluminum coatings. After coating, the parts are generally chromate-treated in accordance with MIL-C-5541. This provides additional protection against corrosion, forms a good base for paint adhesion, and is a common treatment for aluminum alloy surfaces. In virtually all applications, IVD aluminum can replace cadmium of equal thicknesses. It can also be applied thicker than cadmium where part tolerance permits; this results in additional corrosion resistance.

C. SCOPE/APPROACH

The Air Force corrosion control document, MIL-STD-1568, allows the general substitution of IVD aluminum for cadmium on steel. However, the designer or process engineer who considers a substitute for cadmium is invariably faced with uncertainties which are specific to its application. Without first-hand knowledge of all technical ramifications or reference to a readily available technical source, he may be reluctant to change to a different finish. It is often easier to maintain the status quo and thus lose the advantages the substitution may offer such as improved performance and/or the elimination of hazardous waste production. This report, therefore, will provide a readily accessible technical data source on the IVD aluminum and cadmium processes.

Technical information from multiple sources is compiled in this report to provide a comprehensive comparison of the performance of IVD aluminum to both the requirements of MIL-C-83488 and the performance of specific cadmium processes. "Bright," low-embrittlement, vacuum, and diffused nickel-cadmium processes are included in the comparisons as are several different corrosive environments. The inherent properties of IVD aluminum are discussed as well as its effect on substrate mechanical properties and fastener installation characteristics. Information on the versatility of the IVD aluminum coating and rework procedures is also provided.

In addition to the technical data presented in this report, processing costs are addressed and an environmental impact summary is provided. Finally, research and development programs are recommended for those few applications where data is inadequate or additional research is required. As a single data source or handbook, this report should provide virtually all the information necessary to make an informed, sound judgement on the replacement of cadmium processing with IVD aluminum.

SECTION II

COATING PROPERTIES

A. COATING ADHESION

The basic requirement for good adhesion of any finish is proper cleaning. The cleaning procedures for IVD aluminum and cadmium processing are essentially the same; both are adequate and should result in clean surfaces. IVD aluminum, however, has the advantage of an additional, final cleaning procedure which takes place during processing. This glow discharge cleaning (ion bombardment), described in Section I(B), contributes to the excellent adhesion exhibited by IVD coating.

The coating adhesion requirement of military specification MIL-C-83488 for IVD aluminum is comparable to the requirements for electroplated cadmium and vacuum cadmium found in military specifications QQ-P-416 and MIL-C-8837, respectively. All three specifications state that adhesion shall be determined by scraping the surface of the plated article to expose the base metal and examining at a minimum of four diameters magnification for evidence of nonadhesion. As an alternative, a coated test coupon can be clamped in a vise and bent back and forth until coupon fracture occurs. If the edge of the fractured coating can be peeled back, or if separation between the coating and the base metal can be seen at the point of fracture when examined at four diameters magnification, adhesion is not satisfactory. Most metal finish processors use the bend-to-break coupon test method. Under normal conditions, both IVD aluminum and cadmium finishes meet the military specification requirements.

For parts such as fasteners that are coated by barrel tumbling, the substitution of a randomly selected sample in place of a test coupon is allowed (Reference 1). The coated fastener head is crushed in a bench vise. The adhesion requirement is that there be no coating separation from the base metal. IVD aluminum-coated fasteners easily meet this requirement; see Figure 2.

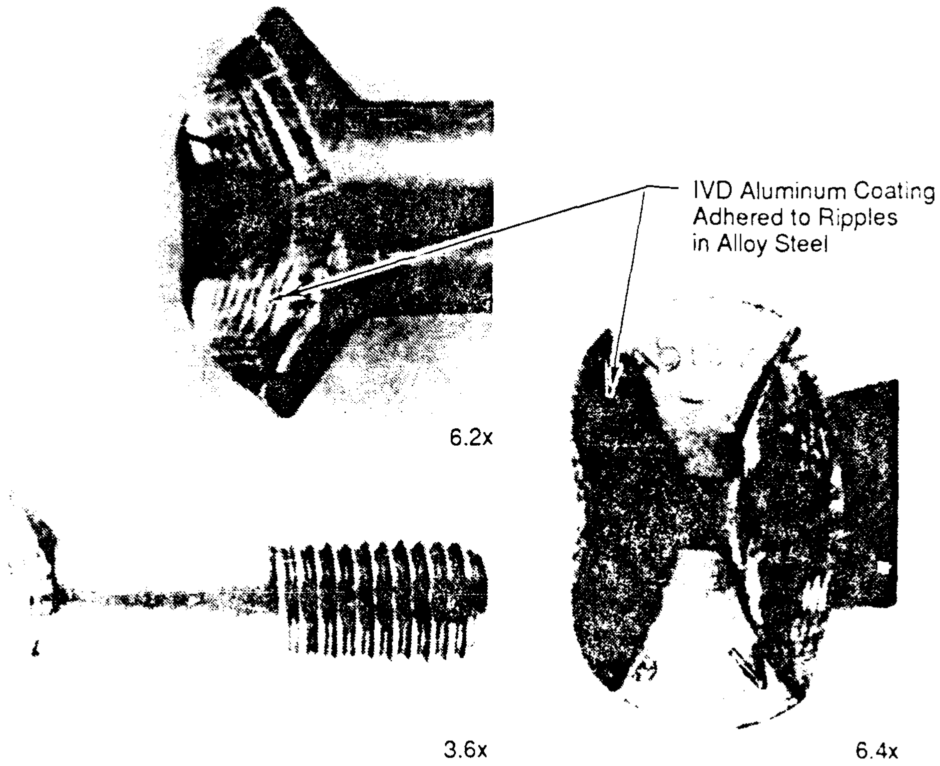


Figure 2. Demonstration of IVD Aluminum Coating Adhesion.

In addition to the required adhesion tests, most IVD aluminum processors burnish (peen) the as-applied IVD aluminum coating with glass beads at 40 psi; this serves as a simple, supplemental adhesion check. IVD aluminum coatings easily withstand burnishing pressures up to 90 psi whereas only 40 psi readily removes vacuum cadmium coatings (Reference 2). Therefore, although IVD aluminum and vacuum cadmium test equally well using bend-to-break coupons, IVD aluminum is far superior to vacuum cadmium in resisting particle impact. Abrasion resistance is discussed in more detail later in Section II(H).

Table 1 shows additional results of adhesion tests on IVD aluminum-coated steel and aluminum alloy panels. The test was conducted to evaluate the effect of chromating on peened and unpeened coating surfaces. Results show excellent adhesion under all conditions (Reference 3).

Another measure of adhesion is the bond tensile strength between the IVD aluminum coating and the substrate. The tensile strength of IVD aluminum, as

TABLE 1. EFFECT OF PEENING AND CHROMATING ON IVD ALUMINUM COATING ADHESION.

Test Specimen/Chromate Conversion Coating	Coating Condition	Adhesion Test						
		Bend-to-Break	Tape Along Fracture	Peen Pressure (psi)				
				20	40	60	80	100
Alodine 1200								
Steel No. 1	Unpeened	E	E	E	E	E	E	M
	Peened	E	E	E	E	E	E	E
Steel No. 2	Unpeened	E	E	E	E	E	E	S
	Peened	E	E	E	E	E	E	E
Aluminum	Unpeened	E	E	E	E	E	E	E
	Peened	E	E	E	E	E	E	E
Iridite 14-2								
Steel	Unpeened	E	E	E	E	E	E	E
	Peened	E	E	E	E	E	E	E
Aluminum No. 1	Unpeened	E	E	E	E	E	E	E
	Peened	E	E	E	E	E	E	E
Aluminum No. 2	Unpeened	E	E	E	E	E	E	E
	Peened	E	E	E	E	E	E	E

Key
E - Excellent Adhesion
S - Trace Non-Adhesion
M - Marginal Non-Adhesion

shown in Table 2, ranges from 8,240 psi to values greater than 10,000 psi using a Sebastian pull tester. In this test (Reference 4), two studs were bonded to each test panel for exerting tensile loads. Two panels were tested for each coating thickness and substrate material.

TABLE 2. ADHESIVE TENSILE STRENGTH OF IVD ALUMINUM COATING.

Specimen	Tensile Strength (ksi)				
Panel One	[a]10.13 9.80	9.32 8.30	[a]10.28 [a]10.31	[a]10.27 9.85	[a]10.32 [a]10.32
Panel Two	[a]10.30 9.66	8.80 9.27	9.94 [a]10.30	[b]6.82 8.24	[a]10.32 [a]10.31

a. The Sebastian adherence tester has a nominal upper limit of 10 ksi. A recorded adherence value of greater than 10 ksi indicates that the stud/coating/specimen interface did not fail.

b. A microscopic inspection indicated that this specimen failed due to substrate surface roughness. The coating did not fail. The stud could not be bonded properly to the surface.

In summary, Table 3 compares the adhesion performance of IVD aluminum and cadmium finishes for various test procedures. In general, IVD aluminum is equal to electroplated cadmium and superior to vacuum cadmium.

TABLE 3. ADHESION OF IVD ALUMINUM VERSUS CADMIUM FINISHES.

Adhesion Test	IVD Aluminum	Electroplated Cadmium	Vacuum Cadmium
Bend-to-Break	Excellent	Excellent	Acceptable
Tape Test	Excellent	Excellent	Acceptable
40 psi Glass Bead Peening	Excellent	Excellent	Fail

B. COATING COVERAGE, UNIFORMITY, AND THICKNESS

The IVD process provides excellent coating coverage and uniformity. It is not limited to line-of-sight coverage and can produce coatings with thicknesses up to several mils. The IVD aluminum coating does not build up or run off sharp edges regardless of coating thickness. Conversely, electroplated cadmium builds up on sharp edges and is normally limited to under 1 mil of plating thickness. Vacuum cadmium is limited to about [illegible] mil of coating thickness due to stress buildup on sharp edges.

Table 4 shows the typical uniformity of IVD aluminum on 4- x 6-inch alloy steel certification panels coated in the IVD aluminum coater at the Warner Robins ALC (Reference 5). The details were affixed to a stationary parts holding rack. MIL-C-83488 requires a minimum coating thickness of [illegible] for Class 3 coatings (nominally 0.3 to 0.5 mil), a minimum of 0.5 mil for Class 2 coatings (nominally 0.5 to 1.0 mil), and a minimum of 1.0 mil for Class 1 coatings (nominally 1.0 to 2.0 mils).

Figure 3 shows the uniformity of IVD aluminum coating on the [illegible]-inch diameter by 15-inch long warhead detail for the Navy's 5-inch [illegible] Laser-Guided Projectile. The detail was fixtured to a rotary parts holding [illegible] rack.

TABLE 4. IVD ALUMINUM COATING THICKNESS AND UNIFORMITY.

Specimen Number	Coating Class	Coating Thickness (mils)[a,b]			
		Side A	Average (Side A)	Side B	Average (Side B)
9	1	1.70, 1.76, 1.82, 1.88, 2.16	1.86	1.22, 1.34, 1.30, 1.34, 1.34	1.31
10		1.76, 1.88, 1.70, 1.82, 1.88	1.81	1.30, 1.30, 1.07, 1.34, 1.34	1.27
11		1.82, 1.88, 1.76, 1.82, 1.95	1.85	1.30, 1.18, 1.30, 1.26, 1.30	1.27
12		1.82, 1.88, 1.64, 1.82, 1.76	1.78	1.39, 1.34, 1.22, 1.44, 1.34	1.35
5	2	0.61, 0.63, 0.54, 0.78, 1.07	0.73	0.59, 0.59, 0.74, 0.51, 0.43	0.58
6		0.83, 0.59, 0.59, 0.63, 0.74	0.68	0.92, 0.51, 0.46, 0.53, 0.59	0.60
7		0.65, 0.73, 0.54, 0.59, 0.69	0.64	0.65, 0.59, 0.48, 0.54, 0.65	0.58
8		0.49, 0.55, 0.51, 0.61, 0.63	0.56	0.65, 0.76, 0.58, 0.66, 0.66	0.66
1	3	0.45, 0.46, 0.43, 0.49, 0.51	0.47	0.38, 0.42, 0.37, 0.40, 0.41	0.40
2		0.37, 0.39, 0.46, 0.47, 0.54	0.45	0.44, 0.40, 0.46, 0.41, 0.49	0.44
3		0.48, 0.47, 0.44, 0.48, 0.44	0.46	0.52, 0.45, 0.33, 0.38, 0.41	0.42
4		0.50, 0.61, 0.45, 0.46, 0.44	0.49	0.38, 0.41, 0.43, 0.54, 0.42	0.44

a Coating thickness measurements were obtained using the Magne-gage instrument

b Measurements were taken 1 in in from each corner and in the center of the 4- by 6-in. panels

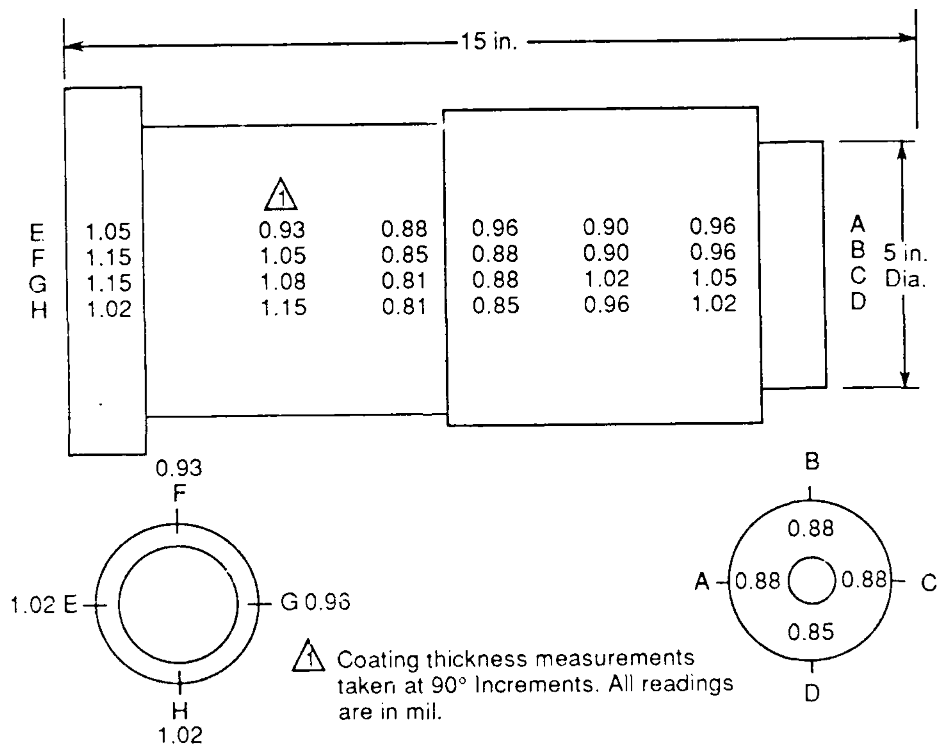


Figure 3. IVD Aluminum Coating Thickness and Uniformity on a Cylindrical Detail.

The uniformity of IVD aluminum on regular surfaces is approximately ± 10 percent of the median thickness. Of equal importance is that the IVD aluminum coating thickness on the edge of a detail is virtually the same as that on the rest of the detail. Figure 4 shows the excellent thickness uniformity between the flat surface and the edge of a gas turbine engine blade. As shown in the figure, there is no buildup or thinning of the coating on sharp edges. The excellent uniformity of IVD aluminum does not depend on coating thickness (Reference 6).

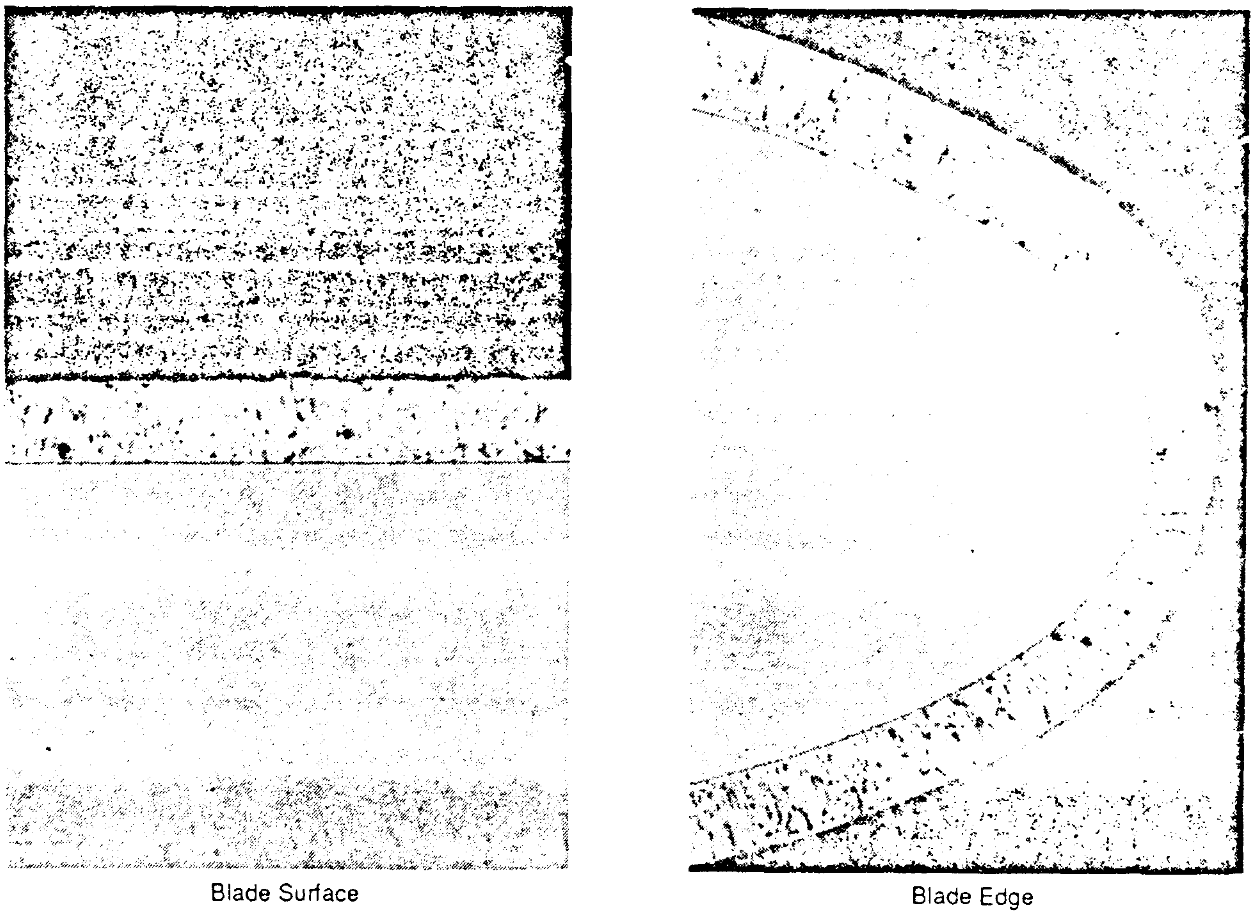


Figure 4. IVD Aluminum Coating Uniformity on a Turbine Blade.

Metallic processing in general is limited in the coverage of internal surfaces. Electroplated cadmium, however, can generally be fixtured with internal anodes for coverage of internal surfaces easier and more economically than IVD aluminum. The IVD aluminum process without special fixturing, will effectively coat internal surfaces to a depth of at least one diameter (Reference 7). An effective coating for most applications is considered to be a 0.3 mil (Class 3) coating or thicker.

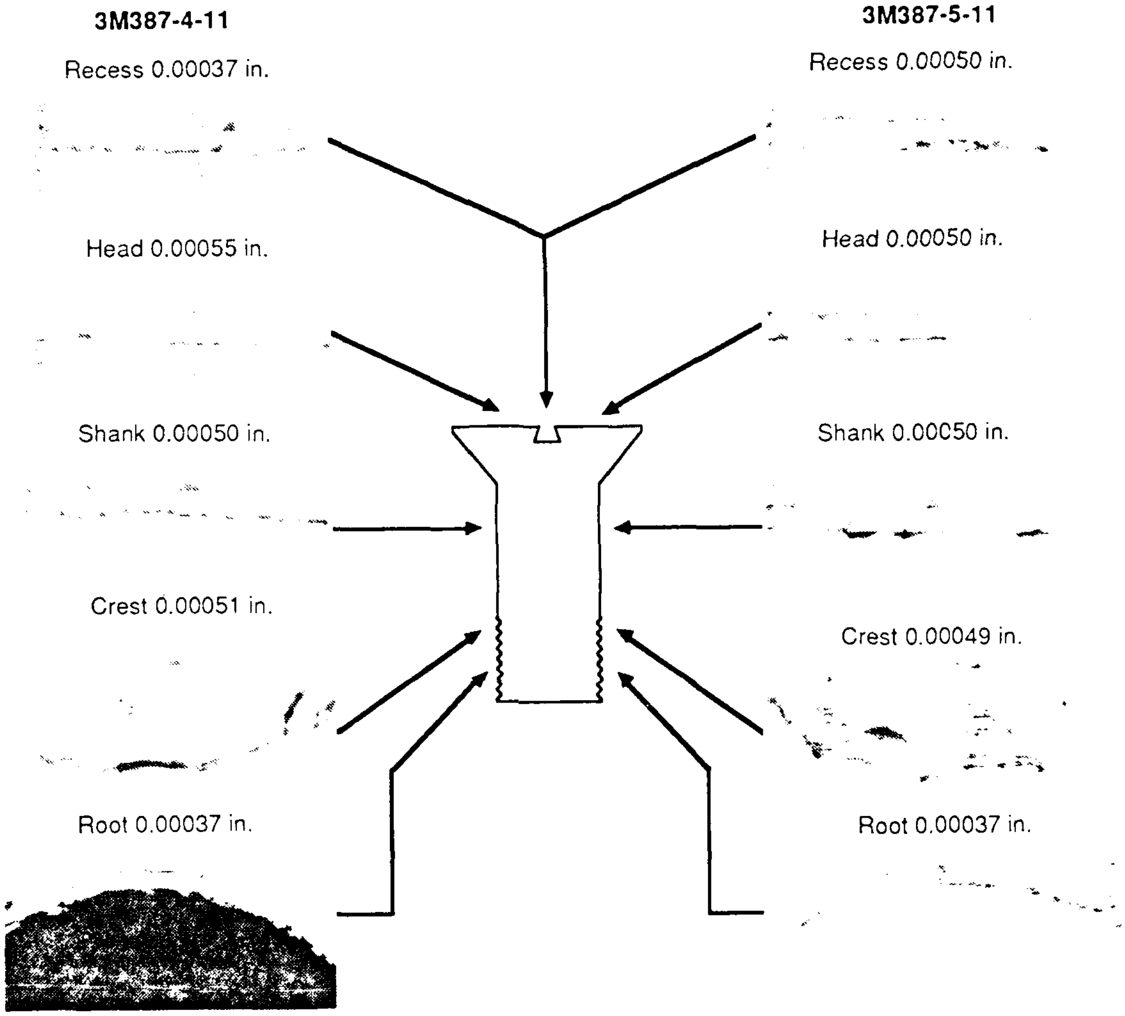
The use of a complementary process, such as sacraficial aluminum-based paints, is recommended for complete coverage of those recess surfaces which exceed the practical limitations of IVD aluminum processing. The use of IVD aluminum in combination with other compatible processes to protect internal surfaces is a recommended research program discussed in Section XII(A).

A barrel accessory for the rack coater can be used for economically coating small details such as fasteners. The excellent IVD aluminum coating uniformity of individual fasteners and the thickness variation throughout the load are shown in Figure 5 and Table 5, respectively (References 8 and 9).

Table 6 summarizes the comparison of coverage, uniformity, and thickness between IVD aluminum and cadmium. IVD aluminum is clearly superior in the area of coating uniformity on edges. It can also be easily applied thicker than cadmium which contributes to corrosion resistance.

C. SURFACE SMOOTHNESS

With the IVD process, the aluminum vapor cloud is partially ionized in the argon gas glow discharge that surrounds the part being coated. This, in addition to collisions with the positively charged argon gas ions, accelerates the aluminum toward the part surface. The result is an adherent coating that replicates the surface of the part and mirrors its surface smoothness. This tendency begins to diminish slightly, however, as the coating thickness increases and its columnar structure becomes more pronounced. Therefore, Thickness Uniformity on Individual Fasteners



Note: *Fasteners randomly selected from production coating run.*

Figure 5. Typical IVD Aluminum Coating Uniformity of Barrel-Coated Fastners.

TABLE 5. IVD ALUMINUM COATING THICKNESS VARIATION THROUGHOUT A PRODUCTION SIZE LOAD OF FASTENERS.

Fastener Number[a, b]	Coating Class	Coating Thickness (mils)	Average Thickness (mils)
1	3	0.44, 0.55, 0.47, 0.34, 0.62	0.48
2		0.77, 0.44, 0.45, 0.62, 0.59	0.57
3		0.77, 0.35, 0.44, 0.71, 0.56	0.57
4		0.65, 0.35, 0.47, 0.44, 0.35	0.45
5		0.87, 0.30, 0.52, 0.44, 0.47	0.42
6		0.66, 0.46, 0.56, 0.61, 0.40	0.54
7		0.37, 0.32, 0.53, 0.43, 0.58	0.45
8		0.61, 0.39, 0.31, 0.30, 0.55	0.43
9		0.36, 0.44, 0.50, 0.33, 0.37	0.40
10	3	0.46, 0.58, 0.38, 0.38, 0.38	0.44

a Fasteners randomly selected from production size run of 150 lb of fasteners/barrel.
b Hexagon head fasteners are 3/8 in. diameter x 2.7 in. long.

TABLE 6. COMPARISON OF IVD ALUMINUM AND CADMIUM PROCESSING.

Finishing Property	IVD Aluminum	Cadmium
Coverage		
External Surfaces	Excellent	Excellent
Internal Surfaces	Limited	Limited
Uniformity		
Smooth Surfaces	Excellent	Excellent
Sharp Edges	Excellent – No Build-Up or Run-Off	Plating Build-Up
Thickness	0.0003 in. to 0.0030 in.	0.0002 in. to 0.0010 in. for Electroplate 0.0003 in. to 0.0010 in. for Vacuum Cadmium

surface smoothness is affected both by part preparation prior to coating as well as by the coating itself. These factors, as well as the part postcoat treatment, will be reviewed in this section.

McDonnell Aircraft Company (MCAIR) evaluated the effect of grit size and grit media on the smoothness of IVD aluminum coatings (Reference 10). Alloy steel panels were grit-blasted with 220-, 400-, and 600-mesh aluminum oxide at a pressure of 50 psi. In addition, some panels were grit-blasted with 220-mesh aluminum oxide, then peened with either BT-10 or the finer BT-13 glass beads. All panels were then IVD aluminum-coated to an average thickness of 0.4 mil. The surface roughness, before and after IVD aluminum coating for various surface preparations, is presented in Table 7. These tests showed that:

o Surface smoothness was virtually unchanged by the relatively thin (0.4 mil) IVD aluminum coating.

o The columnar structure of the IVD aluminum coating became finer and closer knit with smoother substrate surfaces.

TABLE 7. EFFECT OF SUBSTRATE SURFACE PREPARATION ON IVD ALUMINUM COATING SMOOTHNESS.

Surface Preparation	Surface Roughness (μin.)			
	Before IVD		After IVD	
	Average Roughness Height[a]	Total Profile Height[b]	Average Roughness Height[a]	Total Profile Height[b]
Grit Blasted, 220 Aluminum Oxide Grit, 50 psi	36	250	34	180
Grit Blasted, 400 Aluminum Oxide Grit, 50 psi	16	130	14	150
Grit Blasted, 600 Aluminum Oxide Grit, 50 psi	10	100	8	60
Grit Blasted, 220 Aluminum Oxide Grit, 50 psi; Glass Bead Peen BT-10, 40 psi	32	200	34	250
Grit Blasted, 220 Aluminum Oxide Grit, 50 psi; Glass Bead Peen, BT-13, 40 psi	32	220	30	205

a Average Roughness Height is the RMS average deviation in μinches measured normal to the roughness centerline
b *Total Profile Height is the distance in μinches from the lowest point to the highest point on the surface*

In another test, MCAIR determined the effect of grit blasting, IVD coating, and subsequent glass bead peening on the smoothness of IVD aluminum coatings deposited upon smooth steel plates (Reference 11). The steel plates were 16.25 inches in diameter and were machined to a finish having a surface roughness of less than 20 microinches. The surface roughness before and after grit blasting, after coating to approximately 0.6 mil, and after glass bead peening at various pressures is presented in Table 8. These tests demonstrated that:

o Grit blast cleaning with 400-mesh aluminum oxide grit had virtually no effect on the surface finish of the part whereas the standard 220-mesh aluminum oxide grit increased the surface roughness.

o The IVD aluminum coating tended to mirror the surface finish of the part although surface roughness increased on the average 22 percent after coating; this increase is not significant for most applications.

o The surface roughness of the coating increased with glass bead peening because the relatively large impinging glass beads cratered the aluminum coating.

TABLE 8. SURFACE FINISH DATA FOR IVD ALUMINUM PROCESSING.

Grit Blast Data		Surface Roughness (μin. RMS)[a]							Average Coating Thickness (mils)[a]
		Substrate			After Glass Bead Peening (psi)				
Grit Size	Blast Pressure (psi)	Before Grit Blast	After Grit Blast	After Coating	20	30	40	60	
400	35	17/21	19/20	22/22	40/40	—	57/58	—	0.54 0.55
400	35	19/19	19/19	27/26	43/43	—	—	—	0.51 0.54
220	35	19/23	28/29	—	44/43	—	64/68	—	[b]0.57 0.59
220	35	17/21	26/26	39/35	—	53/55	—	—	[b]0.59 0.55
400	35	19/27	18/24	26/28	—	50/52	—	—	0.53 0.56
400	60	—	20/21	22/23	35/43	—	48/54	65/77	0.57 0.60
220	60	—	24/28	25/29	38/40	—	52/56	63/76	0.57 0.58

a First number given is Side 1 of each plate: second number is Side 2.
b The four measurements from the outside edge of these plates were not used to calculate the average thickness since they were not representative due to coating wraparound

After an IVD aluminum coating is glass-bead-peened, the surface roughness is more dependent on the bead size and peening pressure than on part preparation or the coating. BT-10 glass beads produce IVD coatings having a roughness of approximately 50 - 70 microinches at 40 psi. Smoother coatings can be obtained by reducing the glass bead peening pressure and/or media size.

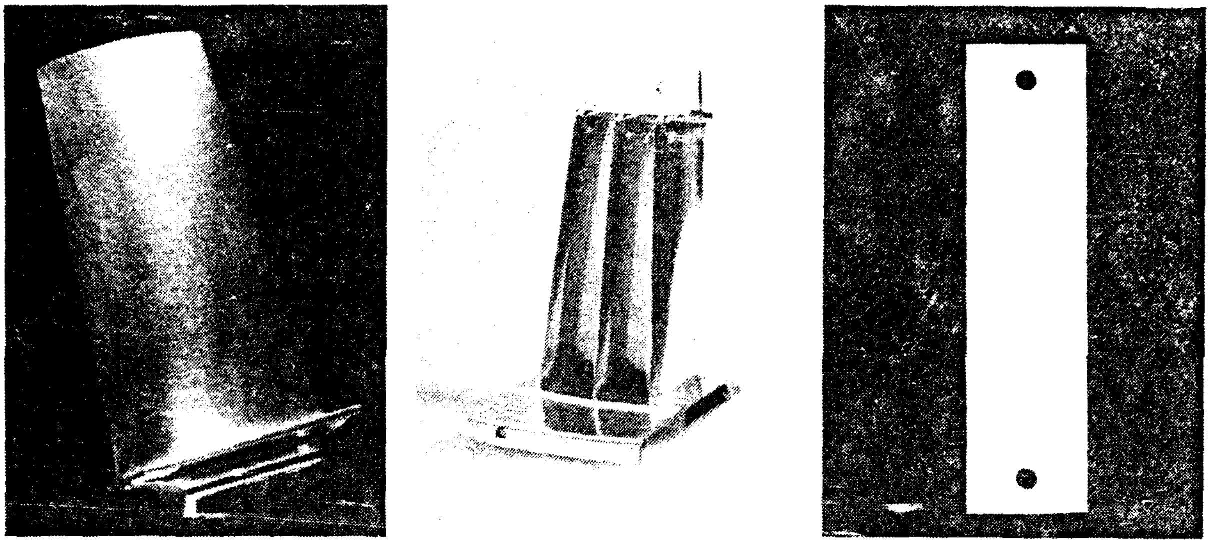
MCAIR evaluated the smoothness of 0.5 mil thick "bright" and low-embrittlement cadmium finishes on 4130 alloy steel panels. The steel panels were grit-blasted with 120-mesh aluminum oxide grit prior to plating. The surface roughness of the steel panels before and after cadmium plating and after a hand burnishing with an abrasive nylon web pad is presented in Table 9. These tests showed that the surface roughness of the parts after plating was not significantly changed, and hand burnishing improved surface smoothness approximately 10 - 40 percent.

TABLE 9. EFFECT OF POSTCOATING TREATMENT ON THE SMOOTHNESS OF CADMIUM PLATING.

Plating	Surface Roughness (μin.)			
	Before Plating[a]	After Plating	Before Plating[a]	After Plating and Burnishing[d]
Bright Cadmium				
Average Roughness Height[b]	87	85	87	79
Total Profile Height[c]	526	519	550	473
Low-Embrittlement Cadmium				
Average Roughness Height[b]	83	87	56	32
Total Profile Height[c]	474	611	374	215

a All panels were grit-blasted with 120 aluminum oxide grit prior to plating.
b Average Roughness Height is the RMS average deviation in μinches measured normal to the roughness centerline.
c Total Profile Height is the distance in μinches from the lowest to the highest point on the surface.
d Burnished with an abrasive nylon web pad.

Smooth coatings, or those that can be polished until they are smooth, are important in jet engine applications. Protective finishes with low drag characteristics minimize fuel consumption and erosion in the airflow sections of engines. MCAIR evaluated several methods of polishing IVD aluminum coatings (Reference 12). Compressor blades, sections of a stator assembly, and alloy steel panels were IVD aluminum-coated and then polished as shown in Figure 6. Photomicrographs of an "as-coated" IVD aluminum surface, a glass-bead-peened IVD aluminum surface, and two polished IVD aluminum surfaces



Compressor Blade - 1.5 x 3.5 in.

Section of Stator Assembly - 2 x 3.5 in.

Steel Panel - 1 x 4 in.

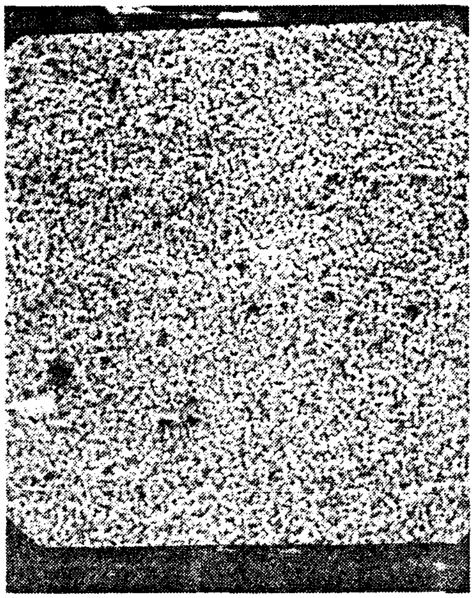
Figure 6. Typical Specimens for Polished IVD Aluminum Coatings.

are presented in Figure 7. Surface finish information and comments on the polishing technique used are given in Table 10. These tests demonstrated that IVD aluminum coating can be polished to a surface finish of less than 20 microinches. This easily satisfies requirements such as Pratt and Whitney Specification 110-4 for coating smoothness on compressor and stator blades. The tests also showed that IVD aluminum coatings can be polished to a surface finish of 10 to 20 microinches without significant removal of the coating, even on the sharp leading or trailing edges of the compressor blades.

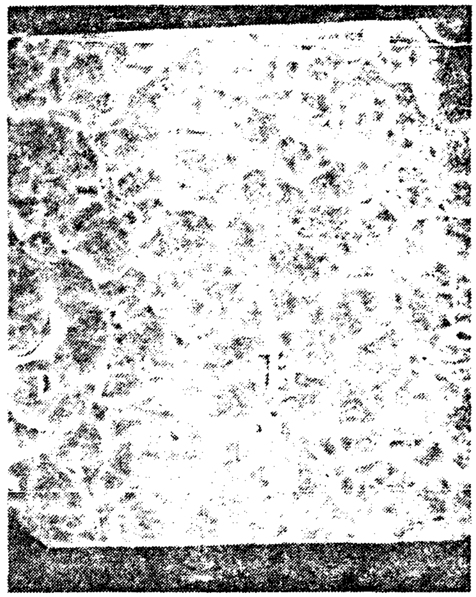
In summary, IVD aluminum coating and cadmium plating replicate the surface finish of the substrate. The effect on surface smoothness of 0.5 mil thick or less IVD aluminum or cadmium finishes is small. Surface smoothness of IVD aluminum coatings decreases as thickness increases. Both IVD aluminum coating and cadmium plating can be polished to produce smoother finishes.

D. TEMPERATURE

IVD aluminum can be used in applications where service temperature requirements are considerably higher than that allowed for cadmium. IVD aluminum can be used at temperatures up to 925°F without any adverse effects.



IVD Aluminum Coating at 39 Microinch Finish (Substrate Surface Cleaned with 220 Aluminum Oxide Grit at 80 psi)



IVD Aluminum Coating Glass Bead Burnished to 62 Microinch Finish (With BT-10 Beads at 20 psi)

IVD Aluminum Coating Polished to 18 Microinch Finish

IVD Aluminum Coating Polished to 10 Microinch Finish

Figure 7. Smoothness of IVD Aluminum Surfaces Before and After Polishing.

TABLE 10. POLISHING DATA FOR IVD ALUMINUM COATINGS.

Finish (μin.)	Polishing Media	Polishing Compound	Comments
18	1/8 in. Microbrite	BB010	Highly Reflective Surface – No Coating Removal on Edges or Corners
36	Ceramic "F" – 50%, 1/8 in. Cylinders and 50%, 3/16 in. Cylinders	550 Flowthrough	Some Removal of Coating at Edges
36	Plastic Cone – 3/4 in. Base, 3/4 in. High, Tumbled	Acid Burnishing Compound	Moderate Polish – No Surface or Edge Damage
10	Steel Balls, Tumbled	Unknown	Removed of Coating at Edges — Excellent Surface Polish
10	Porcelain; 3/16 in. by 1/2 in. Cone	MA-30	Some Removal of Coating at Edges
24	Steel Diagonals – 3/16 in.	Soap	Severe Edge and Corner Coating Removal
40	None		IVD Surface as Coated
62	BT-10 Glass Beads		Burnished at 20 psi

Cadmium melts at 600°F but is usually limited to a 450°F service temperature because of embrittlement that can occur at higher temperatures. Above 600°F, molten cadmium embrittles high-strength steel by grain boundary penetration. It has been shown, however, that cadmium plating can also cause cadmium embrittlement at temperatures as low as 450°F on highly stressed parts.

The higher IVD aluminum service temperature has been a solution to numerous finishing problems involving applications above the 450°F limit for cadmium. The following examples are provided:

o DC-9 Main Landing Gear Piston Brake Flange bolt - For this high-strength steel detail, it was found that cadmium plating melted, chrome plating galled, and nickel plating imposed hydrogen embrittlement problems. The selection of IVD aluminum for this detail provided:

- Acceptable service temperature
- Acceptable installation characteristics
- No hydrogen embrittlement
- Acceptable corrosion resistance

o DC-10 Aft Engine Hangers - For this 4130 alloy steel detail subjected to a 800-900°F service temperature, an aluminum-filled paint-type coating was originally selected over diffused nickel-cadmium as the best available high temperature protective coating. However, one airline reported (Reference 13) that it was necessary to remove and refurbish these mounts every 1500 to 3000 flight hours to retain adequate corrosion resistance. The amount of time the aircraft was out of service for refurbishment was deemed to be prohibitive. As a result, United Airline was the first carrier to install an IVD aluminum-coated mount (see Figure 8).

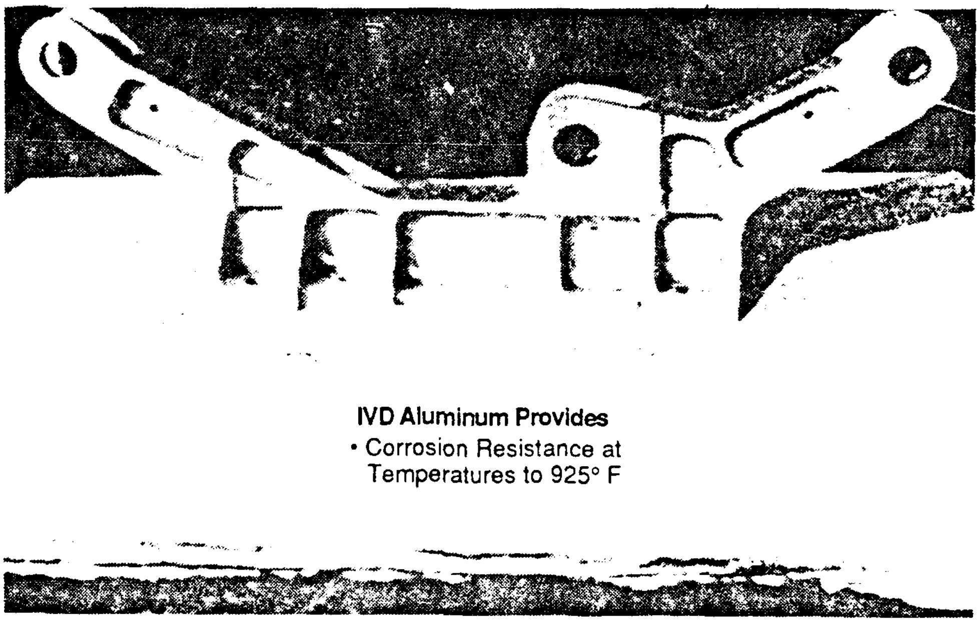


Figure 8. IVD Aluminum-Coated DC-10 Aft Engine Hanger.

Their first report after one year of service, about 3500 flight hours, stated satisfactory performance. This same mount now has over 10,000 flight hours of service without being refurbished (Reference 14). As a result of this performance, Douglas Aircraft issued a letter to all DC-10 carriers suggesting that the engine mounts be refurbished with IVD aluminum (Reference 15). United Airlines, for one, has had their complete DC-10 fleet refurbished with IVD aluminum, and Boeing is using IVD aluminum on the engine mounts of their newest commercial aircraft.

o F-15E Landing Gear Assemblies - The F-15 landing gear components had been cadmium-plated before the F-15E model which is heavier than preceding models. This added weight increased the temperature of some landing gear components during braking action to approximately 450°F. When testing indicated possible cadmium embrittlement conditions, MCAIR recommended a change from cadmium to IVD aluminum. The selection of IVD aluminum eliminated embrittlement concerns with solid metals as well as with hydrogen.

In summary, IVD aluminum has twice the temperature capability of cadmium, and there is no embrittlement concern.

E. ELECTRICAL

IVD aluminum with a supplemental chromate conversion coating is electrically conductive. The coating meets the requirements specified in MIL-C-81706 for the electrical contact resistance of aluminum alloy panels. This specification requires that an aluminum alloy substrate treated with a class 3 material per MIL-C-5541 shall not have a contact resistance greater than 5,000 microhms per square inch as applied, and 10,000 microhms per square inch after exposure to 5 percent salt spray for 168 hours. The electrical measurements are made with an electrode pressure of 200 pounds per square inch (psi) applied to the treated area.

In an effort to further quantify the electrical characteristics of IVD aluminum, conductivity tests were performed by MCAIR (Reference 16). IVD aluminum was applied to glass slides and the conductivity was compared to that of 1100-alloy aluminum wire that had been melted and polished to provide a standard reference. These tests showed that the IVD aluminum coating has approximately 48 percent of the conductivity of the bulk 1100 alloy. This is significant in that bulk aluminum is approximately three times more conductive than cadmium.

The Pratt & Whitney Aircraft Group also performed electrical tests on IVD aluminum and other commercially available finishes (Reference 17). The IVD aluminum coating displayed the lowest electrical resistance within the tested group which included diffused nickel-cadmium. These finishes had to meet a temperature requirement of 500°F which is above the 450°F temperature limit of standard electroplated cadmium. The rough order of magnitude readings were unable to pick up any resistance in the IVD aluminum coatings as shown by a portion of the data presented in Table 11.

TABLE 11. ELECTRICAL RESISTANCE MEASUREMENTS TAKEN ON VANE SPECIMENS.

Finish	Nominal Thickness (mils)	Electrical Resistance (ohms)
IVD Aluminum #1 (With Conversion Coat)	1.5	0
IVD Aluminum #2 (With Conversion Coat)	1.5	0
IVD Aluminum (Without Conversion Coat)	2.0	0
Diffused Nickel-Cadmium	0.3 – 0.5	0.7
E-Nickel-Cadmium	0.7 – 0.8	0.3

Electrical conductivity coupled with the proven corrosion resistance of IVD aluminum coatings has led to its use in applications requiring both capabilities. These are discussed in detail in Section VI(A). IVD aluminum is used for electrical bonding and electromagnetic interference compatibility (EMIC).

F. COMPATIBILITY

The aluminum coating deposited by the IVD process exhibits the same alloy composition as the basic 1100 aluminum alloy evaporant (Reference 18). The 1100 alloy aluminum and cadmium have similar electrolytic solution potentials, -0.83 and -0.82 volts, respectively, when measured against the standard calomel electrode (Reference 19). Since mild carbon steel has a solution potential of -0.58 volts, both IVD aluminum and cadmium provide sacrificial corrosion protection in aqueous environments. Section III compares the corrosion protection provided to alloy steel substrates by IVD aluminum coatings and various cadmium platings.

Cadmium finishes are prohibited on fasteners, fuel lines, and other components where they may come into contact with aircraft fuels (Reference 20). In contrast, IVD aluminum coating is compatible with aircraft fuels and oils. Additional information on the usage of IVD aluminum in contact with fuels, oils, and other fluids is found in Section VI(F).

Cadmium coatings are also prohibited from being in contact with titanium because solid metal embrittlement may result. IVD aluminum is compatible with titanium and is used on aircraft to eliminate dissimilar metal problems between aluminum and titanium structures. Additional information on the usage of IVD aluminum on titanium substrates is found in Section VI(B).

IVD aluminum coatings are more compatible for higher temperature applications than cadmium platings. IVD aluminum coatings can be used at temperatures up to 925°F (compared to 450°F for cadmium). Also IVD aluminum coatings are more compatible for high-strength steel applications because electroplated cadmium causes hydrogen embrittlement problems; high-strength steel parts must be embrittlement relieved by a long, high-temperature bake. *No hydrogen is generated during the* IVD coating process. Discussions on high-temperature usage and on hydrogen embrittlement can be found earlier in Section II(D) and Section IV(A), respectively.

IVD aluminum coatings and cadmium finishes are both compatible with aircraft paint systems. Additional information on paint adhesion of IVD aluminum and cadmium finishes is found in Section II(G).

Table 12 summarizes the compatibility of IVD aluminum and cadmium finishes for the various applications reviewed. As shown, IVD aluminum is more compatible than cadmium.

G. TOPCOAT ADHESION

Topcoats such as paints, sealants, lubricants, etc. are used to improve the performance of the underlying basecoat. For example, topcoats are used to improve corrosion resistance, improve erosion resistance, or change the

TABLE 12. COMPATIBILITY OF IVD ALUMINUM AND CADMIUM FINISHES.

Compatible With	Cadmium Plating	IVD Aluminum Coating
Jet Fuel	No	Yes
Titanium	No	Yes
Hydraulic Fluids and Oils	No	Yes
Temperature		
Low (Up to 450°F)	Yes	Yes
High (450°F – 950°F)	No	Yes
Alloy Steel		
Low Strength	Yes	Yes
High Strength	Yes (Embrittlement Relief Required)	Yes
Aluminum Alloy Structure	Yes	Yes
Paint	Yes	Yes

coefficient of friction of a finish system. The application and successful performance of any topcoat is dependent on basecoat qualities such as coverage, uniformity, and adhesion. IVD aluminum is characterized by excellent adhesion, coverage (non line-of-sight), and uniformity (no buildup or run-off on edges) as discussed in Sections II(A) and (B).

Paint primer and topcoat adhesion are generally of the most interest to military and industrial users. Aluminum alloy surfaces require a chromate conversion coating for acceptable paint adhesion. Therefore, paint adhesion to the IVD aluminum 1100 alloy might be expected to be approximately the same as paint adhesion to any other aluminum alloy as long as both are chromate converion coated. In fact, paint adhesion to IVD aluminum is better than to a wrought aluminum surface because of the structure of the coating. IVD aluminum condenses from the aluminum vapor cloud onto the part surface to form a coating with a uniform, columnar structure; see Figure 9. Although the base layers of aluminum are dense and relatively homogeneous, minute spaces between adjacent columns are formed as the columnar structure grows. As a result, the paint system (and other topcoats) can penetrate into these spaces. Because it has many anchor points, the paint topcoat will adhere to the aluminum basecoat.

Figure 9. Scanning Electron Photomicrograph of the IVD Aluminum Columnar Structure.

MCAIR evaluated the penetration of an epoxy primer into the columnar structure of an IVD aluminum-coated fastener (Reference 21). The fastener was sectioned through the threads and one piece was etched in a 10 percent sodium hydroxide solution to dissolve the aluminum. A scanning electron microscope examination of this etched system showed a skeleton of primer extending well into the IVD aluminum coating. This test verified that topcoat penetration into the IVD aluminum columnar structure did occur to enhance adhesion.

The Boeing Company evaluated paint adhesion on flush head fasteners installed in an aluminum alloy panel. A 0.5-0.8 mil thick layer of BMS 10-79 primer followed by a 1.5-2.0 mil thick layer of BMS 10-60, Type II enamel was applied to the heads of IVD aluminum-coated and cadmium-plated fasteners. The paint system was cured for seven days at 70 $\pm$ 5°F and 40 percent relative humidity. The adhesion of the paint system was evaluated dry and wet, after a 7- day soak in distilled water at 70°F. Boeing reported satisfactory paint adhesion on the IVD aluminum- and cadmium-finished fastener heads, both before and after the water soak (Reference 22).

The real verification of paint adhesion is the tens of thousands of aircraft parts coated with IVD aluminum now in service. Production experience has shown that adhesion of the various paint systems to IVD aluminum basecoats required virtually no in-house rework. In the 12 years painted parts have been installed on aircraft, few, if any, paint adhesion problems have been reported to MCAIR from the military services.

Sometimes cetyl alcohol or dry film lubricants are used on IVD aluminum-coated, threaded parts during the installation of nuts or during the installation of the coated fasteners into close tolerance holes. These and most other commonly used aircraft lubricants are compatible with aluminum. The use of lubricants is discussed in more detail in Section V and XII(C).

Another example where IVD aluminum is used as a basecoat is the application of ceramic sealcoats. Metallic-ceramic coatings per MIL-C-81751 are used to protect steel parts from corrosion by both the ALCs on engine parts and NAVSEA for various marine applications. The two-part coating system consists of a sacrificial aluminum paint basecoat and a ceramic sealcoat. Such coatings include those under the commercial names Alseal®, Xylar® and Sermetel®. The use of IVD aluminum as the sacrificial aluminum basecoat and Xylar® 101 as the ceramic sealcoat produces a metallic-ceramic coating that easily meets the 1000 hour corrosion resistance in neutral salt fog required by MIL-C-81751. Figure 10 shows two alloy steel fasteners, still protected with IVD aluminum/Xylar® 101 after 18,000 hours in 5 percent neutral salt fog.

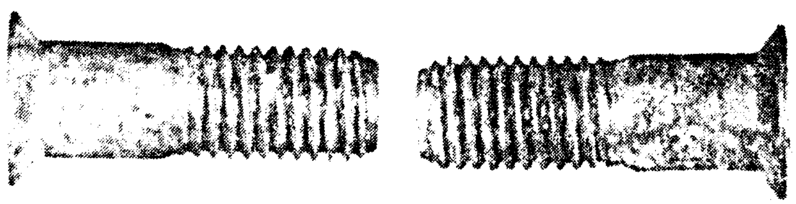


Figure 10. Alloy Steel Fastener With IVD Aluminum and Xylar® Topcoat After 17,952 Hours of Neutral Salt Fog Exposure.

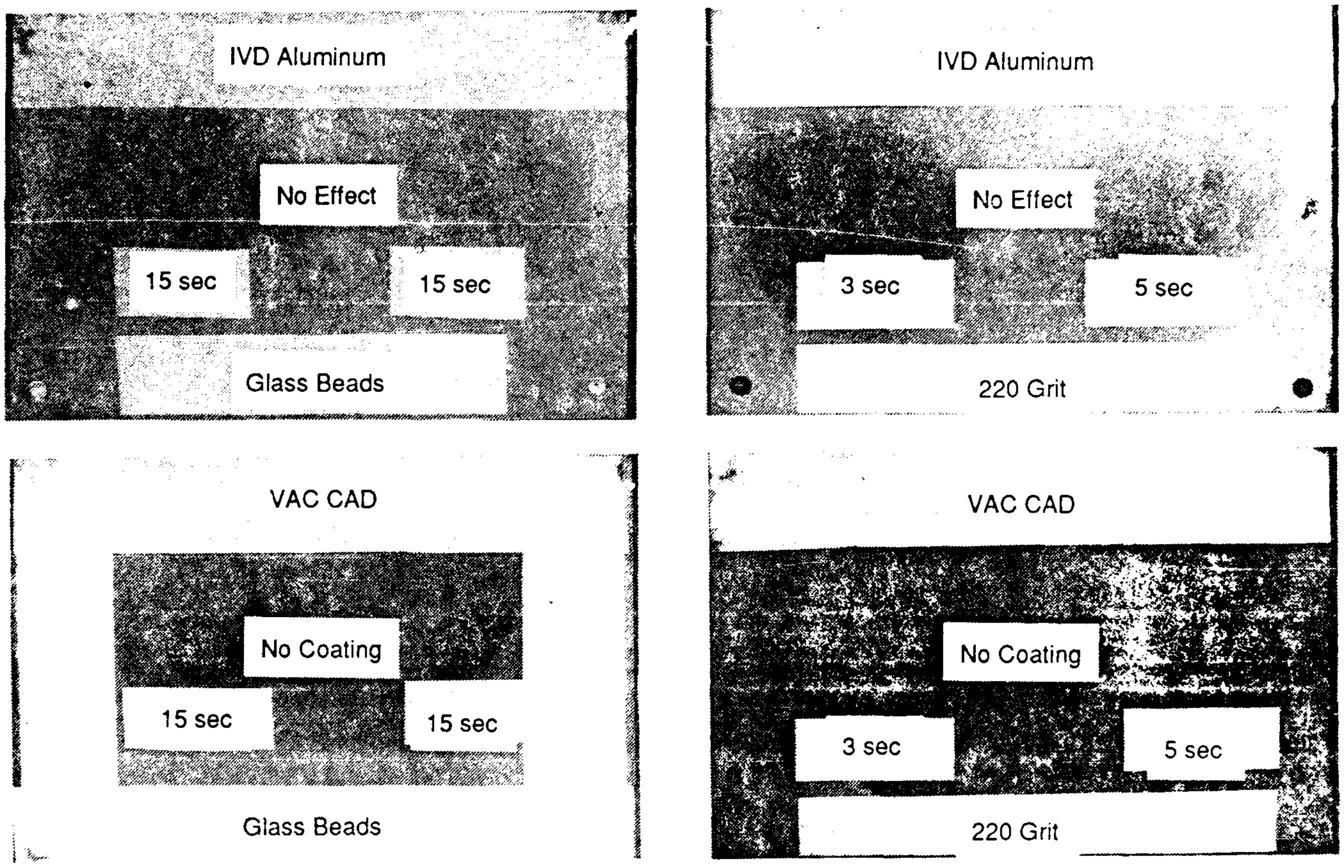
IVD aluminum provides a superior basecoat because it covers uniformly, does not build up or run off edges and adheres significantly better than the aluminum paint basecoats. Insufficient coverage on edges and poor adhesion are field problems for many metallic-ceramic coatings. Initial testing of IVD aluminum/Xylar® 101 by MCAIR (References 23, 24 and 25) shows promise for its use to increase corrosion resistance and enhance erosion resistance.

In summary, the adhesion of topcoats to IVD aluminum can be categorized as excellent. This is due to the inherent qualities of the IVD aluminum coating including its coverage, uniformity, adhesion, as well as its columnar structure which allows topcoat penetration.

H. EROSION RESISTANCE

Both IVD aluminum and cadmium are soft coatings and are not particularly well suited for erosion resistance when used by themselves. Nevertheless, IVD aluminum will outperform vacuum cadmium in resisting abrasive forces and diffused nickel-cadmium when subjected to an erosion/corrosion environment. In addition, IVD aluminum has advantages over cadmium for such an application. First, IVD aluminum can be economically applied thicker than cadmium and, therefore, outlast cadmium when subjected to abrasive forces. Second, IVD aluminum is well suited to being overcoated with abrasion resistant materials. Research to improve the erosion resistance of IVD aluminum with topcoats is discussed in Section XII(B).

Although the adhesion of IVD aluminum and vacuum cadmium test equally well using bend-to-break coupons, IVD is far superior in resisting abrasive particles. This is important in that IVD aluminum and vacuum cadmium coatings are often used on fixed and rotary wing aircraft landing gears, because neither process causes hydrogen embrittlement of the high-strength steel details. However, for such applications, the coatings are subjected to abrasive media during takeoff and landing operations, and the superior IVD aluminum coating will require less maintenance. MCAIR compared the erosion resistance of vacuum cadmium and IVD aluminum using both glass beads and aluminum oxide grit (Reference 26). Figure 11 shows the superiority of IVD aluminum in resisting abrasive particles.



Nozzle 6 in. away at 40 psi

Figure 11. Erosion Resistance of IVD Aluminum Versus Vacuum Cadmium.

In tests conducted by Pratt and Whitney (Reference 17), IVD aluminum with a standard chromate conversion coating was shown to erode faster than the combination coating of diffused nickel-cadmium. However, because the IVD aluminum coating was applied thicker (1.5 mils vs 0.7 mils), there was adequate IVD aluminum remaining at the conclusion of the test. More importantly, IVD aluminum provided better protection to the substrate as the erosion process occurred. With diffused nickel-cadmium, the cadmium erodes very rapidly, leaving only the nickel coating which offers no anodic protection to the substrate. In fact, subsequent testing by Pratt and Whitney showed IVD aluminum to be the best coating tested on 410-alloy steel. Specifically, IVD aluminum outperformed both diffused nickel-cadmium and

Emplate nickel-422/cadmium in an erosion/corrosion environment. This was true for IVD aluminum samples supplied both with and without a standard chromate conversion coating, and a sample supplied with a Chromalloy proprietary conversion coating.

In other testing of coatings for fire retardation of titanium turbine engine blades (Reference 27), the erosion rate of IVD aluminum was shown to be slightly higher than a combination coating of platinum/copper/nickel for 90-degree and 60-degree angles of incidence, but actually lower for the 30-degree angle. Erosion, therefore, was not detrimental to the potential use of IVD aluminum for that application.

In addition to the above, IVD aluminum was successfully tested in both the laboratory and in field service by Westinghouse for use on steam turbine blades (Reference 28 and 29). IVD aluminum has subsequently been put into production for this corrosion/erosion application. These tests are discussed in more detail in Section III(B).

The foregoing establishes that IVD aluminum, although neither it nor cadmium should be considered an abrasive resistant coating, does in fact outperform cadmium in such applications. Further, IVD aluminum is equal to or better than the combination diffused nickel-cadmium coating for corrosion/erosion applications. The primary reason for its superior performance is that it can be applied thicker, and also it provides sacrificial corrosion protection throughout its entire thickness during the erosion process. Therefore, the substitution of IVD aluminum for cadmium should not be impeded because of an erosion resistant requirement except where thin IVD aluminum is required because of tolerance requirements. In this case, abrasion resistance supplemental topcoats offer potential as discussed in Section XII(B).

SECTION III

CORROSION RESISTANCE

A. MIL-SPEC REQUIREMENTS AND TYPICAL TEST RESULTS

Military Specification MIL-C-83488 establishes the requirements for coating low alloy steel, stainless steel, aluminum alloy, and titanium alloy parts with high purity aluminum using the ion vapor deposition process. It identifies three classes and two types of coatings. Class 1 coatings are the thickest and are generally used because they provide the best corrosion resistance. Class 2 and 3 coatings are thinner and are generally used for parts with tolerance limitations such as fastener threads. Type I is "as coated." Type II has a supplementary chromate treatment in accordance with MIL-C-5541 and is recommended because the chromate provides additional corrosion protection. It also forms a good base for paint adhesion and is a common treatment for aluminum surfaces.

MIL-C-83488 requires that "a random sample of two articles shall be taken from any inspection lot at a minimum of once per month or two separately coated specimens (of 4130 alloy steel) shall be prepared (cleaned and coated as a typical production load) to represent an inspection lot." The selected specimens are tested in a neutral salt fog environment per ASTM Method B117 to establish the corrosion resistance of the aluminum coating. MIL-C-83488 specifies that the test specimens "shall show no evidence of corrosion of the basic metal when exposed for the period of time shown in Table 13."

During the early 1970s, the IVD aluminum coating process had advanced at the McDonnell Aircraft Company (MCAIR) from a laboratory to a pilot production status. Full production use began in 1976. Since that time, thousands of parts for the F-4, F-15, F-18 and AV-8B aircraft have been processed. MCAIR has three production coaters in-house to support their extensive use of IVD aluminum coatings. Once a month for each coater, two 4- by 6-inch, 4130 steel specimens are IVD aluminum coated to each of the three thickness classes. These process control specimens are sent to the Quality Assurance Laboratory

TABLE 13. MINIMUM REQUIREMENTS OF MIL-C-83488 FOR NEUTRAL SALT FOG EXPOSURE.

Class	Minimum Coating Thickness (in.)	Salt Fog Test Requirement	
		Type I[a] (hr)	Type II[b] (hr)
1	0.0010	504	672
2	0.0005	336	504
3	0.0003	168	336

a Type I - as coated
b Type II - with supplementary chromate treatment

for corrosion resistance testing. Some 2000 specimens have been tested since 1976 (Reference 30). All of the specimens have met MIL-C-83488 requirements.

In addition to monthly in-house corrosion testing in support of aircraft production, MCAIR also requires that all new suppliers of the IVD aluminum coating process provide specimens for testing. Four IVD aluminum-coated 4-inch by 6-inch, 4130 steel panels are required for each of the three thickness classes. The specimens are submitted to the laboratory to verify that the supplier can produce coatings that will satisfy the corrosion resistance requirements of MIL-C-83488. Since 1976, over 30 supplier coaters have been certified (Reference 31). Once a supplier becomes certified as an approved source, he must perform monthly corrosion resistance tests to the MIL-SPEC requirements. Suppliers have not reported any problems meeting these conditions.

MCAIR's laboratory research with IVD aluminum coatings provides an additional source of corrosion test data. Corrosion resistance has been measured and recorded for most coating cycles conducted in the laboratory. These coating cycles include large numbers of steel prototype parts for MCAIR, other companies, and the military services. Subsequent reports or corrosion performance by these external sources provide an important substantiation of MCAIR testing.

The compilation of information over the past decade from production activities, laboratory evaluations, and independent testing has produced a unique and extensive data base on the corrosion resistance of IVD aluminum. From this data base, a well substantiated, typical performance level for each class of the IVD aluminum coating can be established.

An examination of the MCAIR data base was made for those specimens tested to failure in a 5 percent neutral salt fog environment. Failure is considered to have occurred at the first sign of red rust which results when the IVD aluminum coating is depleted to the extent it can no longer sacrificially protect the steel substrate. Some 900 data points were randomly extracted for 4130 steel test panels representing hand-fixtured details and alloy steel NAS 584 fasteners representing barrel-fixtured details. For the test panels, there are 148 data points for Class 1 coatings, 167 for Class 2, and 56 for Class 3. For the test fasteners, there are 13 data points for Class 1, 237 for Class 2, and 284 for Class 3.

The MIL-C-83488 corrosion resistance requirement and the average time to failure for the three IVD aluminum coating classes are shown in Figure 12. IVD aluminum performs extremely well. Class 1 coatings average approximately

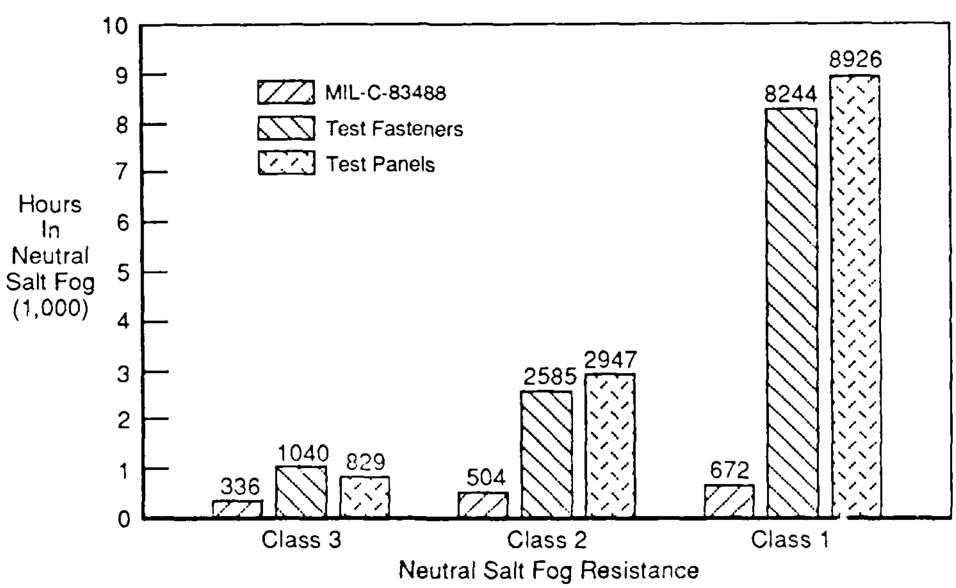


Figure 12. Average Test Results Versus Minimum Requirements of Mil-C-83488.

9000 hours and Class III coatings about 1000 hours in the 5 percent neutral salt fog environment. On the test panels, the average corrosion resistance of Class 1, 2, and 3 IVD aluminum coatings exceeds the requirements of MIL-C-83488 by a factor of 13.2, 5.8, and 2.4, respectively. For the test fasteners, the average corrosion resistance of Class 1, 2, and 3 IVD aluminum coatings exceeds the requirements of MIL-C-83488 by a factor of 12.2, 5.1, and 3.0, respectively. The correlation between the test panels and fasteners close and provides an additional level of confidence in the test data. Figure 13 shows a plot of corrosion-resistance data points for the neutral

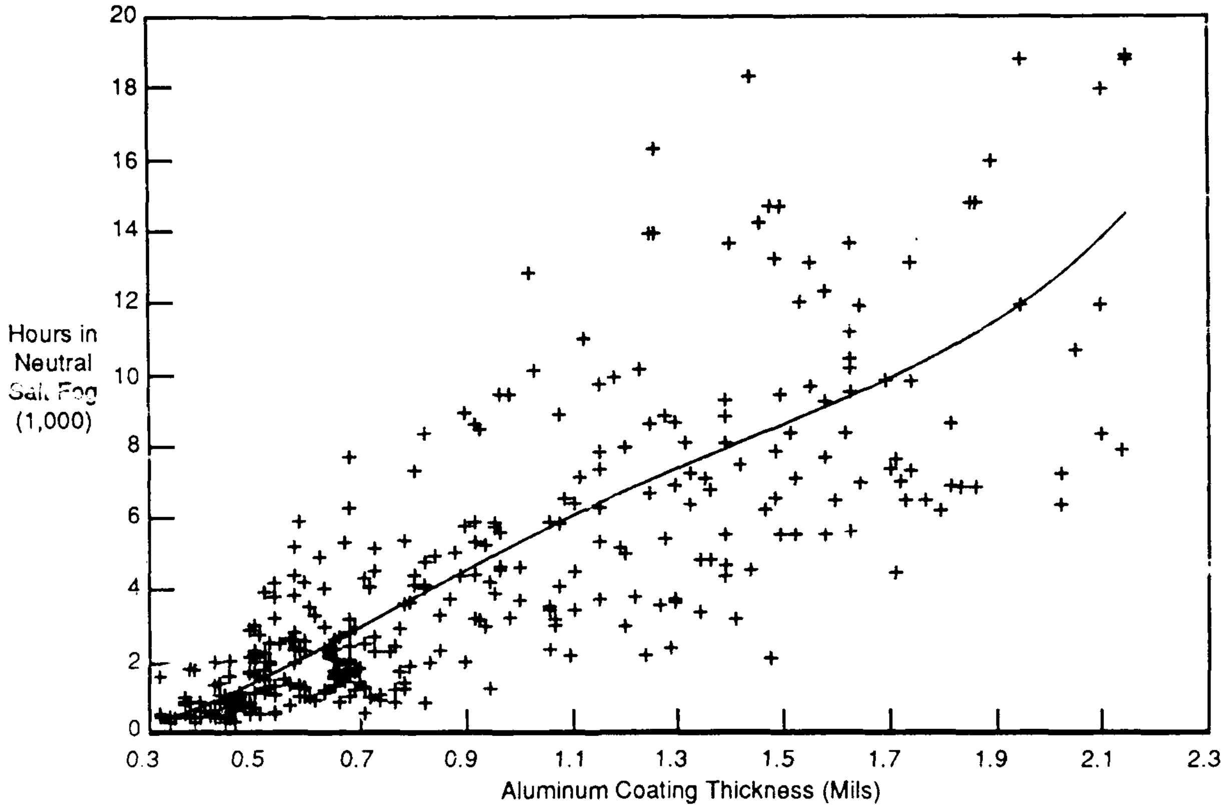


Figure 13. Corrosion Resistance of IVD Aluminum In Neutral Salt Fog.

salt fog environment. The curve fitting the data gives average values of corrosion resistance for the IVD aluminum coating over a wide range of thicknesses. One advantage of IVD aluminum versus cadmium is that it can easily be applied much thicker and therefore provides increased corrosion resistance. As shown from the curve, typical corrosion resistance of IVD aluminum ranges from approximately 5000 hours at 1 mil to 14,000 hours at

2.3 mils. Also note that the lowest data points for the Class 1, 2, and 3 thickness ranges are 2088 hours, 576 hours and 336 hours, respectively. These are all equal to or above the MIL-SPEC requirement. The curve is a useful design tool and also can be used to check the quality of processing procedures. For example, if quality control test values for a particular thickness consistently fall below the curve value, it might be surmised that processing procedures are not up to standard.

B. COMPARISONS TO CADMIUM PROCESSES

The corrosion resistance performance of IVD aluminum has been compared to the various cadmium processes on alloy steel substrates by MCAIR and others, including the military services. The comparisons have generally been made for either neutral salt fog, acidic salt fog, or outdoor environmental exposures. In addition, IVD aluminum and cadmium finishes have been compared in several specialized test environments. These comparisons, lead to the conclusion that IVD aluminum can replace all cadmium processes without exception.

Electroplated cadmium ("bright cad") provides the best corrosion resistance of the cadmium processes and is used for most general applications. The more porous electroplated cadmium process, low-embrittlement cadmium ("dull cad"), and vacuum cadmium are normally used in place of "bright cad" on high-strength steel details to control hydrogen embrittlement. The diffused nickel-cadmium process is normally used for higher-temperature applications (up to 900°F) and/or for applications requiring better erosion resistance. Other cadmium processes, such as titanium-cadmium, usually fall within the range of these four finishes.

The following general statement can be made when comparing the corrosion resistance of IVD aluminum to the most corrosion resistant cadmium process, "bright cad":

For equal thicknesses, "bright cad" protects alloy steel better than IVD aluminum in the neutral salt fog environment. IVD aluminum, however, performs well in this environment and protects alloy steel better than "bright cad" in acidic salt fog environments and in most outdoor environments.

Major advantages of IVD aluminum are its 950°F service temperature and the fact that it does not cause hydrogen embrittlement. Therefore, it can be applied to steel details of all strength levels without limitation. In addition, with the IVD aluminum process, coating thicknesses up to several mils can be applied. Thicknesses are generally limited to a mil or less with the cadmium processes. The added corrosion resistance of thicker IVD aluminum for those applications where part tolerance permits adds to its merits.

1. Neutral Salt Fog Exposure

IVD aluminum performs well in neutral salt fog as documented in Section III(A). However, "bright cad" at equal thickness performs even better. On examining test reports comparing the corrosion resistance of IVD aluminum versus the other three cadmium processes, some conflicting conclusions were encountered. In general, however, it can be concluded that the performance of IVD aluminum is essentially equal to those processes in the neutral salt fog environment.

o IVD aluminum versus "bright cad" - The following abbreviated summaries of test results reported by others show satisfactory performance for both finishes in the ASTM B117 neutral salt fog environment:

(1) SPS Technologies compared "bright cad" and IVD aluminum on MS21250-04-018 alloy steel bolts for 500 hours in neutral salt fog. SPS reported that the IVD aluminum coating and the cyanide (bright) cadmium plating provided equal protection to the alloy steel bolts (Reference 32).

(2) The Carter Carburetor Division of ACF Industries exposed alloy steel springs protected by both IVD aluminum and "bright cad" to

neutral salt fog for a total of 920 hours. Similar to the SPS report, Carter Carburetor reported that IVD aluminum and bright cadmium coatings provided equal protection to the springs (Reference 33).

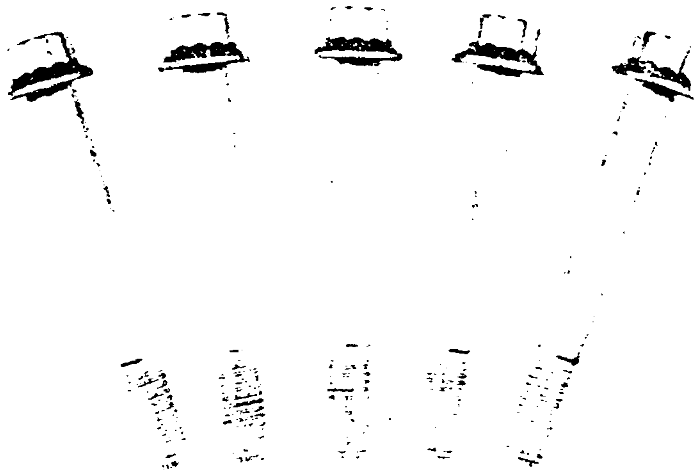
o IVD aluminum versus low-embrittlement cadmium - Vacuum processes such as IVD aluminum and vacuum cadmium do not cause hydrogen embrittlement and are often used to protect high strength steel parts from corrosion. A "dull cad" plating with proper postprocess baking for embrittlement relief is also satisfactory. Landing gears are typical of the high-strength components protected with these processes.

Landing gear finishes are often subjected to scratches or the development of voids from debris hitting the gears during takeoffs and landings. These damaged areas can then become corrosion sites. MCAIR tested IVD aluminum and "dull cad" finished panels with defects of various sizes purposely introduced to simulate what might occur on landing gears. These parts were then subjected to neutral salt fog testing for 528 hours. MCAIR reported in Reference 34 that IVD aluminum was slightly superior to the "dull cad" plating.

o IVD aluminum versus vacuum cadmium - Like "dull cad," vacuum cadmium is primarily used for high-strength steel applications. The performance of IVD aluminum compares favorably with vacuum cadmium in neutral salt fog. The following are test report summaries:

(1) SPS Technologies compared IVD aluminum and vacuum cadmium on H-11 bolts for 500 hours. They reported in Reference 32 that the IVD aluminum coating provided better protection to the high strength steel bolts. The test specimens after exposure are shown in Figure 14.

(2) MCAIR compared IVD aluminum- and vacuum-cadmium-coated 4130 alloy steel panels in neutral salt fog for 500 hours. A portion of the coatings had been purposely removed in a diagonal strip across each panel surface to observe the sacrificial nature of the coatings. In this case, the test results showed that the vacuum cadmium coating provided more protection to the steel panels than the IVD aluminum coating (Reference 35).



IVD Aluminum-Coated H-11 Bolts

Vacuum-Cadmium-Coated H-11 Bolts

Figure 14. IVD Aluminum- and Vacuum-Cadmium-Finished Alloy Steel Fasteners After 500 Hours of Neutral Salt Fog Exposure.

o IVD aluminum versus diffused nickel-cadmium - Nickel-cadmium is primarily used for engine applications. The following abbreviated summaries are from company reports comparing IVD aluminum and nickel-cadmium in the neutral salt fog environment:

(1) Pratt & Whitney Aircraft tested IVD aluminum and nickel-cadmium finishes on AMS 6322 bolts for 1800 hours per ASTM B117. They reported in Reference 36 that the nickel-cadmium plated fastener was severely corroded. Corrosion of the IVD aluminum coated fastener did occur, but it was not as severe.

(2) In another test, Pratt & Whitney compared IVD aluminum and nickel-cadmium finishes on AMS 6322 and AMS 6304 bolts. The bolts were exposed to neutral salt fog for 768 hours. Again, IVD aluminum provided better protection.

(3) Boeing tested IVD aluminum and nickel-cadmium finished H-11 steel bolts for 336 hours in neutral salt fog. They reported that IVD aluminum and nickel-cadmium provided equal protection to the H-11 bolts. In the same report (Reference 37), it was stated that for longer-term salt fog exposures, nickel-cadmium provided better corrosion protection than IVD aluminum.

(4) Westinghouse Electric and Southern California Edison ran a 4-year study for the Electric Power Research Institute to identify finishing systems that would alleviate corrosion-related fatigue failures of low-pressure steam turbine components. IVD aluminum and nickel-cadmium were two of the 26 protective finishes evaluated on steel panels in a neutral salt fog environment. In addition, IVD aluminum and nickel-cadmium were evaluated on steam turbine blades for 1 year in a Southern California Edison power plant.

Westinghouse and Southern California Edison reported that IVD aluminum provided the best corrosion protection of all the finishes evaluated (Reference 28). (IVD aluminum provided slightly better protection than the nickel-cadmium). Subsequently, IVD aluminum was judged better than nickel-cadmium after 1 year of exposure in the operating steam turbine (Reference 29).

2. Acidic Salt Fog Exposure and Specialized Environments

The actual in-service environment is not always best simulated by testing in neutral salt fog. At many commercial and military industrial sites, for example, there are emissions of sulfur dioxide from smokestacks. The sulfur dioxide emissions, in the presence of either fresh or salt water, accelerates the corrosion rate due to the formation of acids. One of the more severe environments is that for an aircraft carrier operating in a tropical zone where the combinations of high temperatures, sulfur dioxide emission, and salt water are extremely corrosive.

MCAIR uses a sulfur dioxide (SO_2) salt fog environment developed by the Naval Air Development Center (NADC) to represent acidified salt environments. Test conditions are created by injecting SO_2 gas into a 5 percent neutral salt fog chamber for one hour each six hours. The salt fog chamber is maintained at a temperature of 95°F.

For equal thicknesses, IVD aluminum significantly outperforms all types of cadmium finishes in the SO_2 salt fog environment. This is exemplified by the following test report summaries:

a. MCAIR tested Class 3, Type II, IVD aluminum coated and Class 2, Type II, "bright cad" plated NAS 564 steel fasteners for 58 hours in SO_2 salt fog. They reported that IVD aluminum provided better protection to the steel fasteners (Reference 38). Test specimens are shown in Figure 15.

b. NADC tested IVD aluminum coated and "bright cad" plated steel fasteners from Navy stock in SO_2 salt fog for 504 hours. They reported that IVD aluminum provided better corrosion resistance (Reference 39).

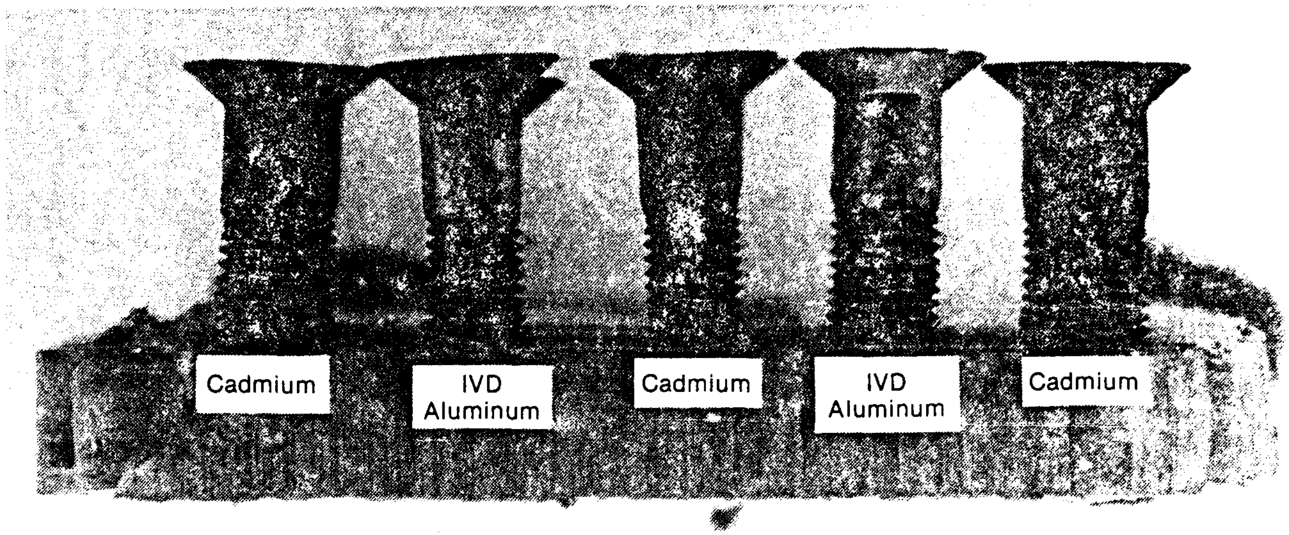


Figure 15. IVD Aluminum- and Electroplated-Cadmium-Finished Fasteners After 58 Hours of SO_2 Salt Fog Exposure.

c. In another test (Reference 40), MCAIR compared IVD aluminum and vacuum cadmium on 4130 alloy steel panels exposed for 144 hours to SO_2 salt fog. The vacuum cadmium coated panel had completely rusted well before the conclusion of the test. In contrast, the same thickness IVD aluminum coated panel showed no corrosion. The panels after 144 hour exposure are shown in Figure 16.

d. MCAIR also compared Class 1 and 2, Type II, IVD aluminum and Class 1, Type II, vacuum cadmium coated panels with and without a supplemental topcoat of paint in SO_2 salt fog exposure. The paint system consisted of an epoxy primer and two coats of polyurethane topcoat. In this test, IVD aluminum provided more than twice (384 hours versus 168 hours) the protection to the low alloy steel panels that were not painted. On the painted vacuum cadmium coated panels, red rust was observed leaching from a spot after 3973 hours in the acidic salt fog. No red rust was observed on the painted IVD aluminum coated panel and the test was concluded (Reference 41).

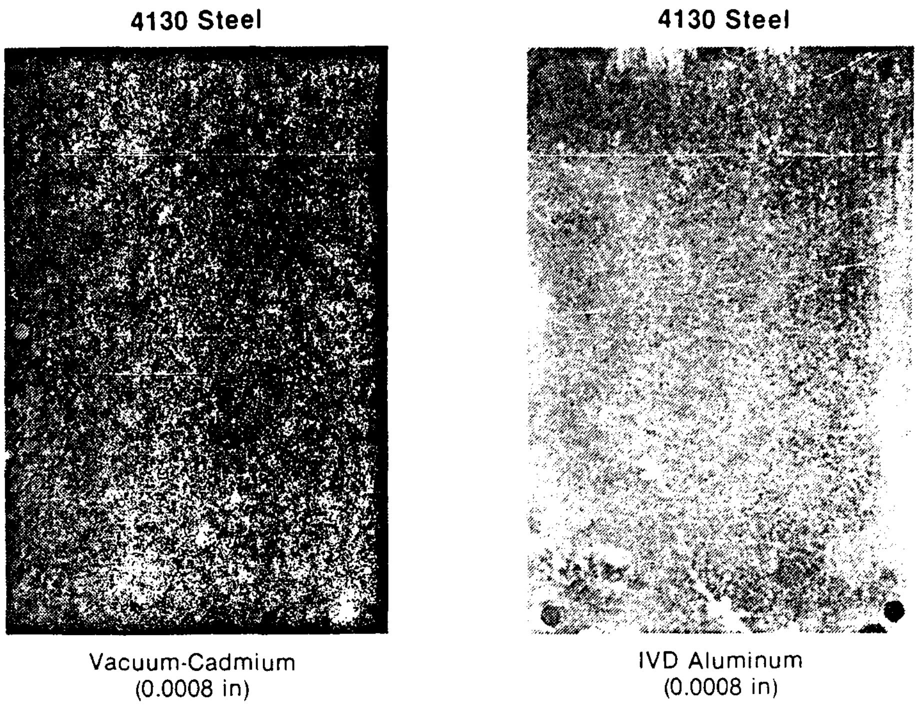


Figure 16. IVD Aluminum- and Vacuum-Cadmium-Finished Steel Panels After 144 Hours of SO_2 Salt Fog Exposure.

Some companies have evaluated IVD aluminum and other corrosion resistant finishes under special test conditions designed for their specific applications. In these specialized environments, IVD aluminum has been found to perform as good as or better than other finishes. The following test report summaries compare the performance of IVD aluminum and cadmium:

a. Pratt & Whitney Aircraft conducted a program (Reference 17) to investigate the performance of 16 corrosion resistant finishes for AMS5504 stators. These finishes were applied to 410 steel panels and exposed to the following specialized test environment:

(1)(a) 168 hours in neutral salt fog per ASTM B117
(2)(b) 24 hours in air at 500°F
(3)(c) 168 hours in neutral salt fog per ASTM B117

Pratt & Whitney reported that IVD aluminum was the best of the 16 corrosion resistant finishes evaluated for this application. Figure 17 shows panels with IVD aluminum and nickel-cadmium at the conclusion of the test.

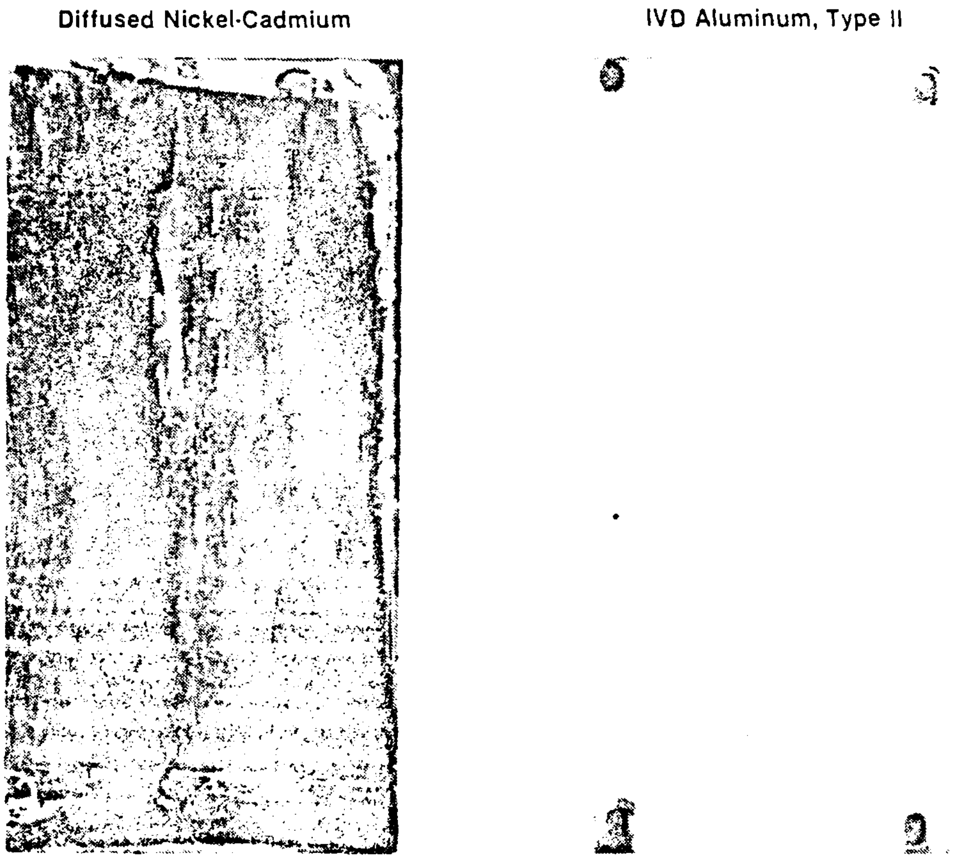


Figure 17. IVD Aluminum- and Diffused Nickel-Cadmium-Finished Alloy Steel Panels After 336 Hours of Cyclic Neutral Salt Fog/Oven Exposure.

b. In other tests, Pratt & Whitney compared IVD aluminum and nickel-cadmium on both vane and shroud segments, and on fasteners. The test specimens were subjected to the following neutral salt fog/heat exposure cycle:

(1)(a) 168 hours in neutral salt fog per ASTM B117

(2)(b) 20 hours in air at 400°F

Testing ended after a total of 535 hours for the vane and shroud segments and after 544 hours for the fasteners. Pratt & Whitney reported that IVD aluminum and nickel-cadmium provided equal protection to the segments but that nickel-cadmium appeared to protect the fasteners better (Reference 36).

c. Carter Carburetor Division of ACF Industries exposed IVD aluminum and "bright cad" processed alloy steel springs to a corrosive oil environmental test for 700 hours. For this specialized environment, Carter Carburetor reported that IVD aluminum provided better protection (Reference 33).

3. Outdoor Exposure Including Service Reports

Because of their "real-world" nature, outdoor exposure tests and in-service reports provide some of the most important corrosion resistance comparisons between IVD aluminum and cadmium. IVD aluminum is compared most often to "bright cad" in these tests. Results vary depending on environment; but, in general, an equal thickness of IVD aluminum outperforms "bright cad." Since "bright cad" is normally the best performing cadmium process, it can be inferred that IVD aluminum would have performed even better compared to other cadmium processes. The following summaries are provided from test reports:

a. In 1968 MCAIR began a long term comparison of the corrosion resistance of IVD aluminum, vacuum cadmium, and "bright cad" finishes on 4130 alloy steel panels in an outdoor environment (Reference 42). The substrate metal was purposely exposed in a diagonal strip across each panel surface to observe the "sacrificial" protection provided by the finishes. The panels were placed on the rooftop of a building adjacent to the St. Louis airport and exposed for over 12 years.

After 6 months, it became obvious that IVD aluminum was providing the best protection. After 4 years, the vacuum cadmium coating was totally depleted, and the "bright cad" plating was nearly depleted which allowed most of the panel surface to rust. The IVD aluminum coating continued to protect the panels as shown in Figure 18.

After 12 years, IVD aluminum continued to provide excellent protection against corrosion. Long before that time, the vacuum cadmium and "bright cad" finishes had been totally depleted allowing the 4130 panel to severely rust. The panels after 12 years are also shown in Figure 18.

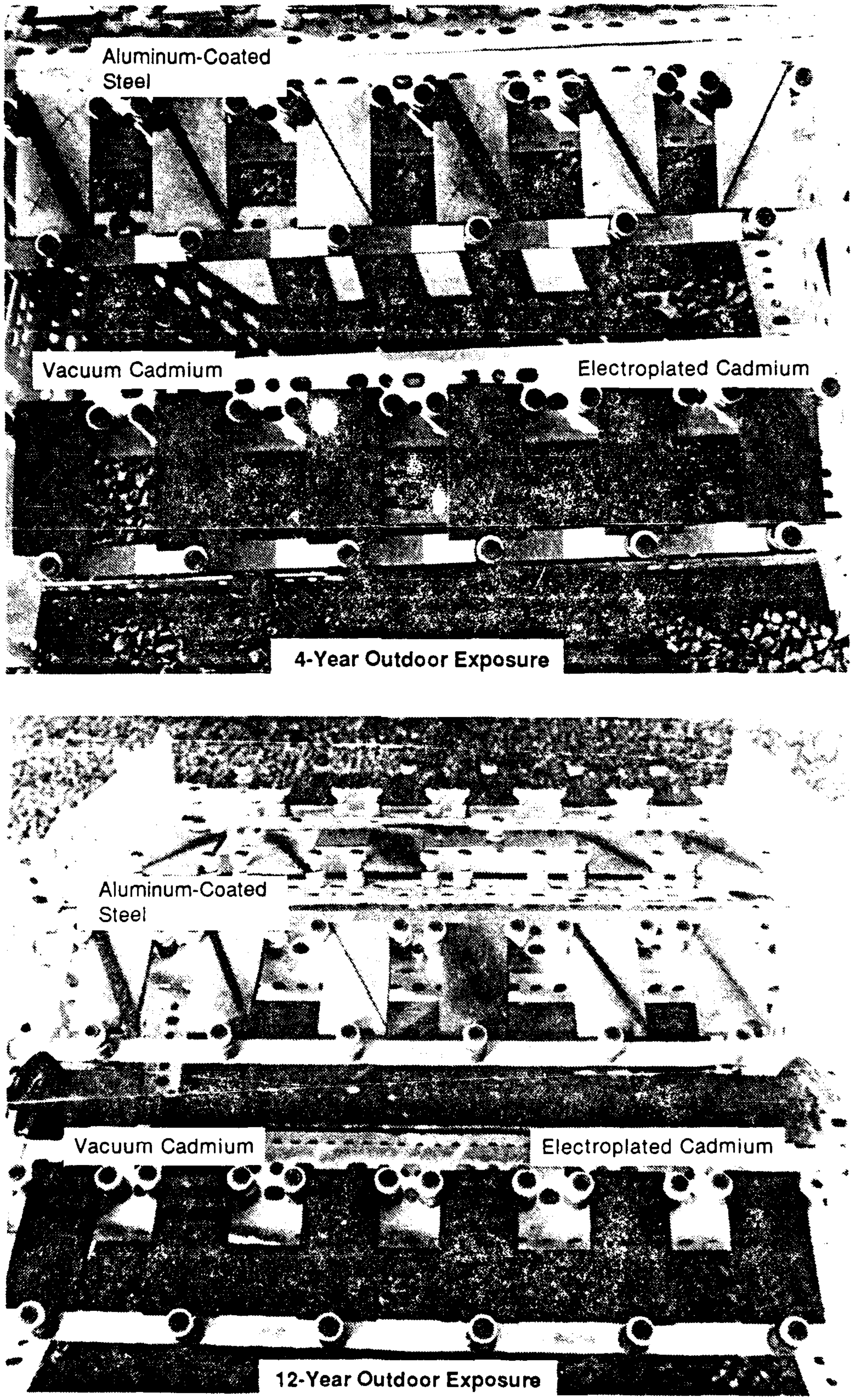


Figure 18. IVD Aluminum- and Cadmium-Finished Alloy Steel Panels After St. Louis Outdoor Exposure.

b. The Air Force Materials Laboratory conducted an in-service evaluation of a variety of corrosion resistant finishes applied to NAS 1203 alloy steel fasteners. The test fasteners were installed on four operational C-141 aircraft. The panels containing the fasteners were located either on the top, side, or bottom of the C-141 aircraft to provide a variation of in-service environmental exposures. The test period was for two years. The Air Force report (Reference 43) stated that the IVD aluminum coated fasteners showed a marked superiority over "bright cad" plated fasteners.

c. A second evaluation (Reference 44) of different corrosion preventive finishes on fasteners was performed by the USAF Airlift Center for the Air Force Wright Aeronautical Laboratory. NAS 1203 alloy steel fasteners were again installed on a C-141 aircraft. The test period was for two years and nine months. The four C-141 aircraft accumulated an average flight time of 2309 hours. The test again showed that IVD aluminum provided more protection.

d. The Naval Ship System Engineering Station evaluated nine finishes applied to fasteners and exposed to both coastal and shipboard environments. They reported that IVD aluminum provided more protection to the steel fasteners than "bright cad" (Reference 45).

e. In similar but unrelated tests, NADC had several corrosion resistant finishes applied to steel panels which were also exposed to a shipboard environment. Their test showed that both "bright cad" and "dull cad" provided better protection to the steel panels than IVD aluminum (Reference 46).

f. In a later test (Reference 47), NADC compared IVD aluminum and "bright cad" for two different shipboard exposures. NADC reported that in this later test, IVD aluminum provided better protection to the steel fasteners than "bright cad."

g. Douglas Aircraft and United Airlines evaluated IVD aluminum and diffused nickel-cadmium on engine mounts during airline service. They found that for this high temperature application (over 800°F exposure), IVD aluminum offered considerably more protection (Reference 48).

The following general conclusions regarding the comparative corrosion resistance provided by equal thicknesses of IVD aluminum and cadmium on alloy steel substrates are reiterated:

- "Bright cad" performs best in neutral salt fog. IVD aluminum also performs well in this environment.

- IVD aluminum outperforms all of the cadmium processes in acidic environments. It also provided better protection in the specialized environments reviewed.

- IVD aluminum outperforms the cadmium processes in most outdoor exposure tests. IVD aluminum excels in those service environments where atmospheric pollutants form acidic conditions.

It should also be restated that IVD aluminum can easily be applied thicker where part tolerance permits, and that thicker IVD aluminum coatings provide additional corrosion resistance.

Table 14 summarizes the findings in comparing IVD aluminum and cadmium for the three most familiar test environments. It shows that IVD aluminum easily satisfies the demands of a corrosion resistance finish to replace all cadmium processes, including the "bright cad," "dull cad," vacuum cadmium, and diffused nickel-cadmium finishes.

TABLE 14. COMPARATIVE CORROSION RESISTANCE PERFORMANCE.

Environment	IVD Aluminum	Electroplated Cadmium	Low-Embrittlement Cadmium	Vacuum Cadmium	Nickel-Cadmium
Neutral Salt Fog	Good	Excellent	Good	Good	Good
SO_2 Salt Fog	Excellent	Poor	Poor	Poor	Poor
Outdoor Exposures	Excellent	Good	Fair/Good	Fair/Good	Fair/Good

C. GALVANIC COMPATIBILITY OF IVD ALUMINUM-COATED ALLOY STEEL FASTENERS IN ALUMINUM ALLOY STRUCTURE

Numerous tests have been conducted showing the excellent corrosion resistance of IVD aluminum coated alloy steel substrates, including fasteners; see preceding discussion. However, there is an equal if not more important consideration when selecting a finish for alloy steel fasteners installed in aluminum alloy structure. This important consideration is galvanic compatibility of the coated fastener to the aluminum structure. Without galvanic compatibility, pitting or exfoliation corrosion often occurs in such areas as the fastener countersinks. This corrosion problem is hard to detect, expensive to repair, and can lead to structural failure.

The use of IVD aluminum on steel (and titanium) fasteners provides optimum galvanic compatibility with aluminum alloy structure. This has been verified in tests comparing the relative protection provided by aluminum and electroplated cadmium. As is normal with corrosion testing, there is some variation and scatter in the test data. Definite conclusions can be drawn, however, comparing both the protection of the installed fastener and the protection afforded the aluminum alloy structure.

In tests conducted by MCAIR (Reference 38), IVD aluminum and electroplated cadmium finished NAS 584 alloy steel fasteners were installed in anodized, 7178 aluminum alloy blocks.

The fasteners were from the same lot, had the same finish thickness, and the same installation torques. The fastener-block assemblies were then exposed to either a 5 percent neutral salt fog or to an acidic, sulfur dioxide (SO_2) salt fog environment.

In the ASTM B117 neutral salt fog environment, the test results showed that:

- o IVD aluminum protects the aluminum alloy countersink better than cadmium; IVD aluminum is more galvanically compatible.

o Cadmium protects the steel fastener better than IVD aluminum; both finishes exceeded MIL-SPEC requirements.

Figure 19 shows the fastener-block assemblies after 2500 hours of exposure. The heads of the IVD aluminum coated fasteners are more corroded than the heads of the cadmium plated fasteners. However, the countersinks in

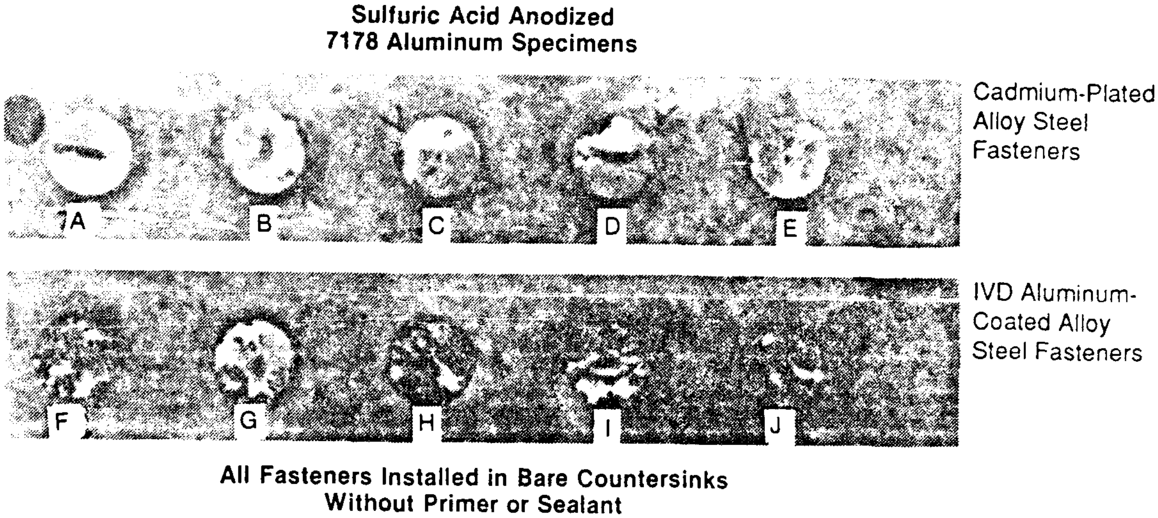


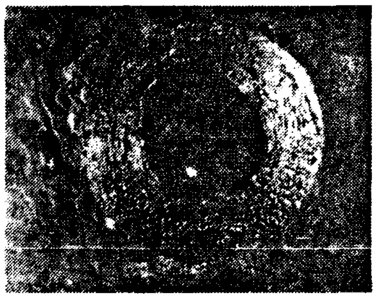
Figure 19. Aluminum Alloy Specimens (With Aluminum-Coated/Cadmium-Plated Fasteners Installed) After 2,500 Hours of Neutral Salt Fog Exposure.

the aluminum alloy panels in which the IVD aluminum-coated fasteners were installed are not nearly as corroded (pitted) as those countersinks in which the cadmium plated fasteners were installed; see Figure 20. Most of the corrosion was down in the countersink and very little around the periphery. Only two of the countersinks occupied by IVD aluminum coated fasteners showed significant amounts of corrosion. All five of the countersinks occupied by cadmium plated fasteners were severely corroded. In this case and most service applications, it would be easier to replace fasteners than to repair or replace structure.

In the SO_2 salt fog environment established by the Naval Air Development Center, test results showed that:

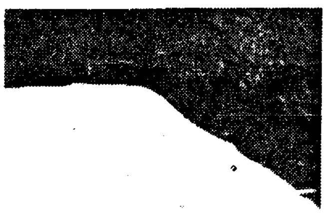
100 x

100 x



6 x

Countersink Occupied by Cadmium-Plated Fasteners



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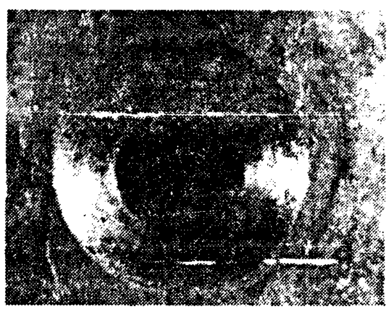

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Countersink Occupied by IVD Aiuminum-Coated Fastener

Figure 20. Aluminum Alloy Countersinks After 2,500 Hours of Neutral Salt Fog Exposure.

o IVD aluminum protects the aluminum alloy countersink better than cadmium.

o IVD aluminum protects the steel fastener better than cadmium.

Figure 21 shows that the cadmium plated fasteners are more severely corroded than the IVD aluminum coated fasteners after 168 hours. These

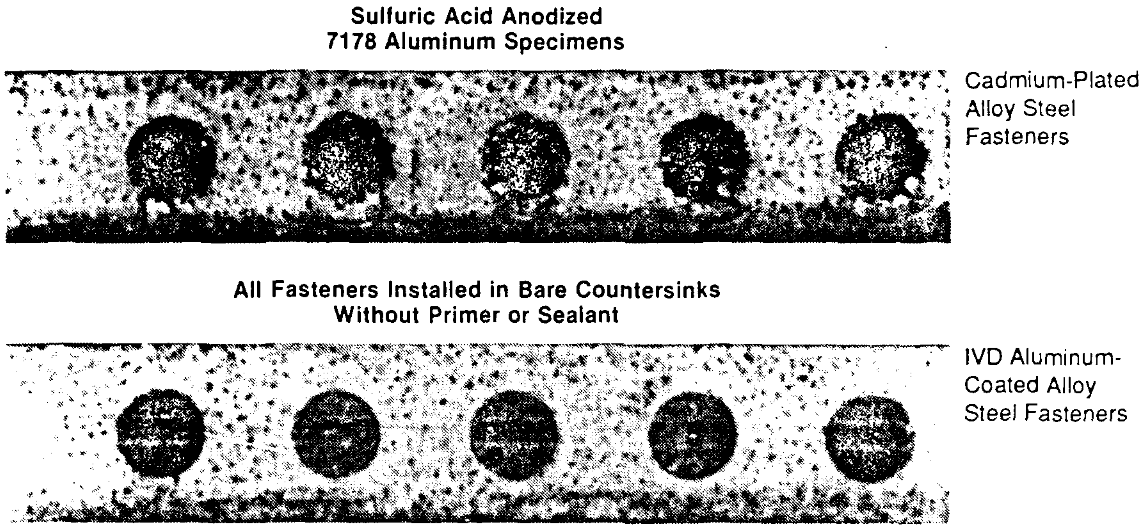


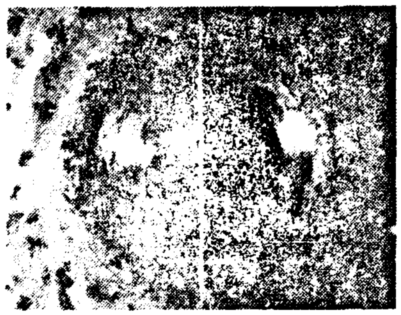
Figure 21. Aluminum Alloy Specimens (With Aluminum-Coated/Cadmium-Plated Fasteners Installed) After 168 Hours of SO_2 Salt Fog Exposure.

fasteners were from the same lot of cadmium plated fasteners that withstood 2500 hours in neutral salt fog. Figure 22 shows substantial pitting in and around the periphery of the countersinks occupied by cadmium plated fasteners and only minor defects in the countersinks occupied by the IVD aluminum coated fasteners after 168 hours.

In addition to testing in neutral and SO_2 salt fog environments, MCAIR also completed four outdoor exposure tests comparing the corrosion resistance of IVD aluminum and electroplated cadmium on steel fasteners installed in anodized, 7075 aluminum alloy blocks (Reference 49). Randomly selected NAS 584 alloy steel fasteners from various lots were used in two of the tests. NAS 1203 alloy steel fasteners were used in the other two tests. Thicknesses and installation torques were equal for both the aluminum and cadmium protected fasteners.

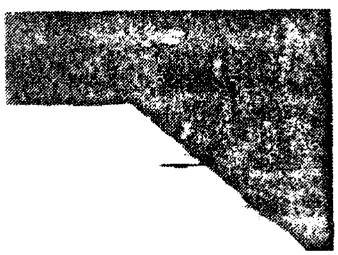
100 ×

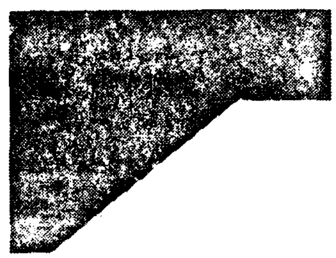
100 ×



6 ×

Countersink Occupied by Cadmium-Plated Fasteners





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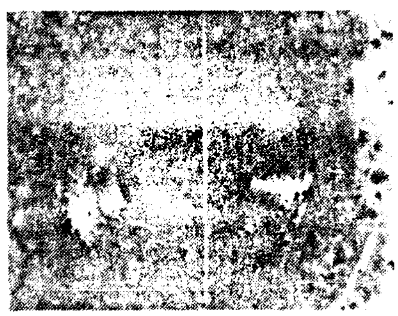


6 ×

Countersink Occupied by IVD Aluminum-Coated Fastener

Figure 22. Aluminum Alloy Countersinks After
168 Hours of SO_2 Salt Fog Exposure.

In addition to testing in neutral and SO_2 salt fog environments, MCAIR also completed four outdoor exposure tests comparing the corrosion resistance of IVD aluminum and electroplated cadmium on steel fasteners installed in anodized, 7075 aluminum alloy blocks (Reference 49). Randomly selected NAS 584 alloy steel fasteners from various lots were used in two of the tests. NAS 1203 alloy steel fasteners were used in the other two tests. Thicknesses and installation torques were equal for both the aluminum and cadmium protected fasteners.

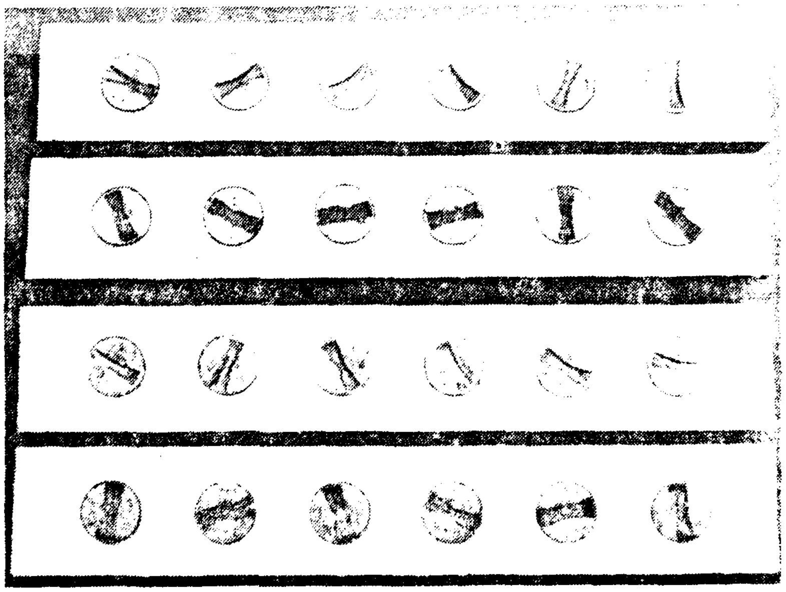
In the St. Louis outdoor (industrial) environment, test results showed that:

- o IVD aluminum protects the aluminum alloy countersink better than cadmium.

- o IVD aluminum protects the steel fastener better than cadmium.

Whereas the time to failure (depletion of protective finish) varied, the following failure sequence was identical in all four tests:

First: Corrosion staining in the recess area of the aluminum coated fasteners, Figure 23



IVD Aluminum - Static

IVD Aluminum - Reuse

Cadmium - Static

Cadmium - Reuse

Figure 23. Corrosion Stains In Recess Area of IVD Aluminum-Finished Fasteners After 24 Months of St. Louis Outdoor Exposure.

Second: Depletion of the cadmium plating around the periphery of the fastener head, Figure 24

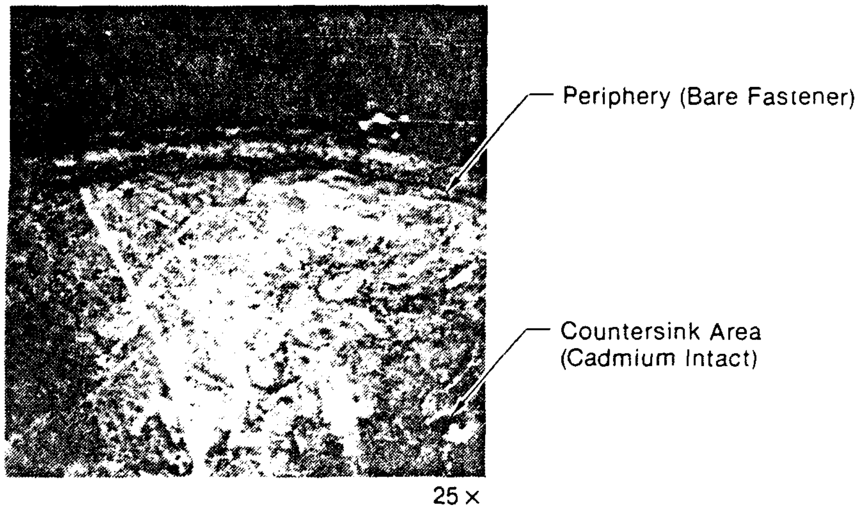


Figure 24. Cadmium Depletion on Periphery of Fastener Head.

Third: Depletion of the cadmium plating from the periphery of the head inward towards the head recess area, Figure 25

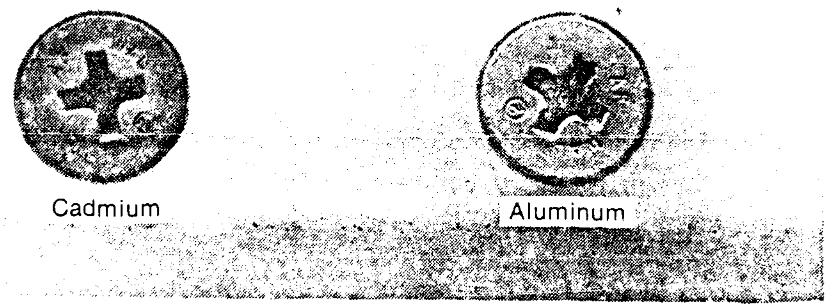


Figure 25. Cadmium Depletion Advancing on Fastener Head.

Fourth: Total depletion of the cadmium plating on the fastener head, Figure 26

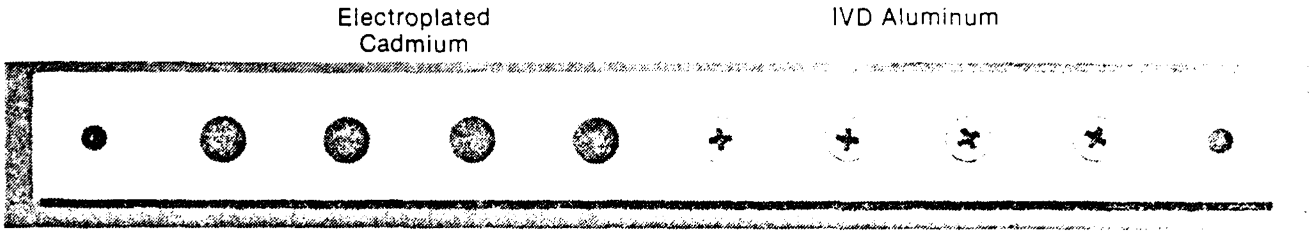


Figure 26. Corrosion Resistance of IVD Aluminum- Versus Electroplated-Cadmium-Finished Fasteners.

In all four tests, the only damage to the aluminum-coated fasteners at the time the cadmium-plated fastener heads were completely corroded were stains in the head recess. In all cases, the IVD aluminum coating was intact on the critical outer periphery of the fastener head and had completely protected the aluminum alloy countersink. In contrast, there was considerable damage to the aluminum countersinks occupied by the cadmium-plated fasteners. Table 15 summarizes the test results.

TABLE 15. IVD ALUMINUM COMPARED TO ELECTROPLATED CADMIUM ON STEEL FASTENERS INSTALLED IN ALUMINUM ALLOY STRUCTURES.

Environment	Relative Protection by Fastener Finish	
	Steel Fastener	Aluminum Countersink
5% Neutral Salt Fog	Cadmium Best	IVD Aluminum Best
SO_2 Salt Fog	IVD Aluminum Best	IVD Aluminum Best
Industrial Outdoor	IVD Aluminum Best	IVD Aluminum Best

SECTION IV

EFFECT ON MECHANICAL PROPERTIES (SUBSTRATES)

A. HYDROGEN EMBRITTLEMENT/STRESS CORROSION CRACKING

Strength levels of 180,000 psi and greater are common for high-strength steel alloys used to meet the design objectives of modern aerospace products. The higher strength levels of these materials have increased their susceptibility to catastrophic failure from hydrogen embrittlement and stress corrosion cracking.

The problems associated with hydrogen embrittlement have existed for years and are well-documented. Hydrogen diffusion into the substrate during processing is the source of the problem. The use of processes that either limit the quantity of free hydrogen available for diffusion into the substrate or negate its presence provide the best solution to the problem.

Sources of free hydrogen include cleaning or pickling operations utilizing an acid bath and electroplating operations. When high-strength steel details are subjected to such sources, stringently controlled embrittlement relief baking cycles must be relied upon to reverse or minimize the embrittlement mechanism.

The IVD aluminum process is embrittlement-free. Precleaning consists of solvent cleaning followed by mechanical cleaning with dry aluminum oxide grit. The IVD aluminum coating is applied in a hydrogen free vacuum environment. Therefore, there is no need for costly embrittlement relief procedures nor is there the risk of catastrophic failure due to processing.

Vacuum cadmium is applied in a similar hydrogen-free environment. However, electroplated cadmium processes all require embrittlement relief baking cycles as shown in Table 16.

TABLE 16. PROCESSES REQUIRING HYDROGEN EMBRITTLEMENT RELIEF.

Process	Type of Process	Free Hydrogen Available	Embrittlement Relief Required
IVD Aluminum	Vacuum	No	No
Vacuum Cadmium	Vacuum	No	No
"Bright" Cadmium	Electroplate	Yes	Yes
Low-Embrittlement Cadmium	Electroplate	Yes	Yes
Diffused Nickel-Cadmium	Electroplate	Yes	Yes

In addition to the absence of hydrogen during its application, IVD aluminum has also been shown to resist post hydrogen embrittlement and stress corrosion cracking. In comparative testing, IVD aluminum generally is equal to or better than other metallic coatings. This testing is summarized in Table 17. Even more important, there have been no reported failures attributed to post hydrogen embrittlement or stress corrosion cracking of IVD aluminum coated production parts in over 12 years of field service experience.

As shown in Section III, the successful use of IVD aluminum on high strength steel details is well established. Tens of thousands of production parts have been processed and put into service with no reported problems. Numerous test reports by MCAIR and other companies continue to show IVD aluminum providing outstanding corrosion resistance with no embrittlement concerns and, therefore, no costs due to embrittlement relief. Figure 27 shows typical high strength steel production parts coated with IVD aluminum. They range from small, barrel-coated springs to larger, individually racked parts like landing gear details and rocket motor cases.

b. FATIGUE

Aluminum coatings applied by the IVD process have no detrimental effect on fatigue or other substrate mechanical properties. The coating has a tightly knit columnar structure and is soft and ductile with properties virtually identical to those of pure aluminum; see Section II(b). Also, the deposited aluminum coating forms a mechanical bond rather than an intermetallic bond which can reduce fatigue properties. Lastly, there are no discernable batch-to-batch variations in the properties of the IVD aluminum coating since

TABLE 17. SUMMARY OF HYDROGEN EMBRITTLEMENT AND STRESS CORROSION CRACKING TESTS ON HIGH-STRENGTH STEEL DETAILS.

Test Name	Specimen	Heat Treat (ksi)	Load	Environment	Coating	Conversion Coated	Embrittlement Relieve	No of Specimens	Average Time to Failure	Tested By	References
High-Strength Steel Coating Systems	4340 Stress Ring	260 - 280	90% Ultimate Tensile Strength (UTS)	Room Followed by 5% Neutral Salt	IVD Al L E Cad	Yes Yes	No No	2 3	30 Days (No Failure) 9 hr 30 Days (No Failure) 7 hr	Douglas 1973	50
Compare IVD and Vac Cad High-Strength Steel	300M Notch Tensile	280 - 300	80% Notch Tensile Strength (NTS)	Alternate Immersion SOW Adjusted to pH of 3 With Acetic Acid	VD Al IVD Al Vac Cad Bare	Yes No Yes	No No No	3 3 3 3	15.6 hr 2.7 hr 2.0 hr 64.0 hr	McDonnell Aircraft 1975	51
Effect of IVD Al on Embrittlement of High-Strength Steel	300M 4330V 98BV40 300M 4330V 98BV40 Notch Tensile	280 - 300 220 - 240 280 - 300 280 - 300 220 - 240 280 - 300	75% NTS	Room	IVD Al IVD Al IVD Al Vac Cad Vac Cad Vac Cad	Yes Yes Yes No No No	3 of 6 3 of 6 3 of 6 Yes Yes Yes	6 6 6 3 3 3	200 hr (No Failures) 200 hr (No Failures) 1 Failure at 3.5 hr 200 hr (No Failures) 200 hr (No Failures) 200 hr (No Failures)	McDonnell Aircraft 1975	52
Investigation of Failed 98BV40 Specimen	98BV40 Notch Tensile	280 - 300	75% NTS With 1% Increase Each 7 hr	Room	IVD Al Vac Cad IVD Al Bare	Yes Yes Yes	Yes Yes No	[illegible] [illegible] [illegible] 2	51[illegible] hr at [illegible]% NTS 487 hr at 89% NTS 444 hr at 67% NTS 366 hr at 82% NTS	McDonnell Aircraft 1976	53
Effect of IVD on High-Strength Steel	4340M Notch Tensile	260 - 280	75% NTS	Room	IVD Al	Yes	No	1[illegible]	200 hr (No Failures)	Boeing 1981	54
Compare IVD and L E Cad on 300M Steel	300 M Notch Tensile	280 - 300	75% NTS Immersion 3.5% Neutral Salt	Alternate Immersion 3.5% Neutral Salt	IVD Al L E Cad Bare	Yes Yes	No No	3 3 3	123 hr 89 hr 6 hr	McDonnell Aircraft 1981	55
Hydrogen Embrittlement of Springs	ASTM-A-401 Alloy Steel Springs	304 - 315	Compression (Cyclic and Static)	Room	E P Cad E P Cad E P Zinc E P Zinc IVD Al	Yes Yes Yes Yes Yes	No Yes No Yes No	4 4 4 4 8	100% Failed [illegible]% Failed 100% Failed [illegible]% Failed [illegible]% Failed	FMC 1980	[illegible]
Hydrogen Embrittlement of Snaprings	1080 Alloy Steel Snaprings		Expanded Onto Bar (Static)	Room - 16 Days 5% Salt - 20 Days	E P Cad E P Cad E P Zinc E P Zinc IVD Al	Yes Yes Yes Yes Yes	No Yes No Yes No	50 50 50 50 100	No Failures No Failures 13 Failures No Failures No Failures	FMC 1980	56
Ivadizer Aluminum Plating (Cadmium Substitute)	ASTM A-228 Alloy Steel Springs	306 - 339	180° Bend (22 hr) Compression (22 hr) Compression (1,000 hr) Compression (1,000 hr)	Room Room Fuel Pump Test Stand (Oil) Corrosive [illegible]	IVD Al E P Cad IVD Al E P Cad IVD Al E P Cad IVD Al E P Cad	Yes Yes Yes Yes Yes Yes Yes Yes	No Yes No Yes No Yes No Yes	4 4 4 4 4 4 4 4	No Failure No Failure No Failure No Failure No Failure No Failure [illegible] No Failures 1 Failed at [illegible] hr 1 Failed at [illegible] hr 1 Failed at [illegible] hr 1 Failed at [illegible] hr 1 Failed at [illegible] hr	[illegible]	[illegible]
Stress Corrosion Cracking	300M [illegible]	280 - 300	Compression	Alternate Immersion 3.5% Neutral Salt	IVD Al [illegible]	Yes [illegible]	No No	[illegible]	[illegible] Days [illegible] No Failures [illegible] Days [illegible]	[illegible]	5[illegible]

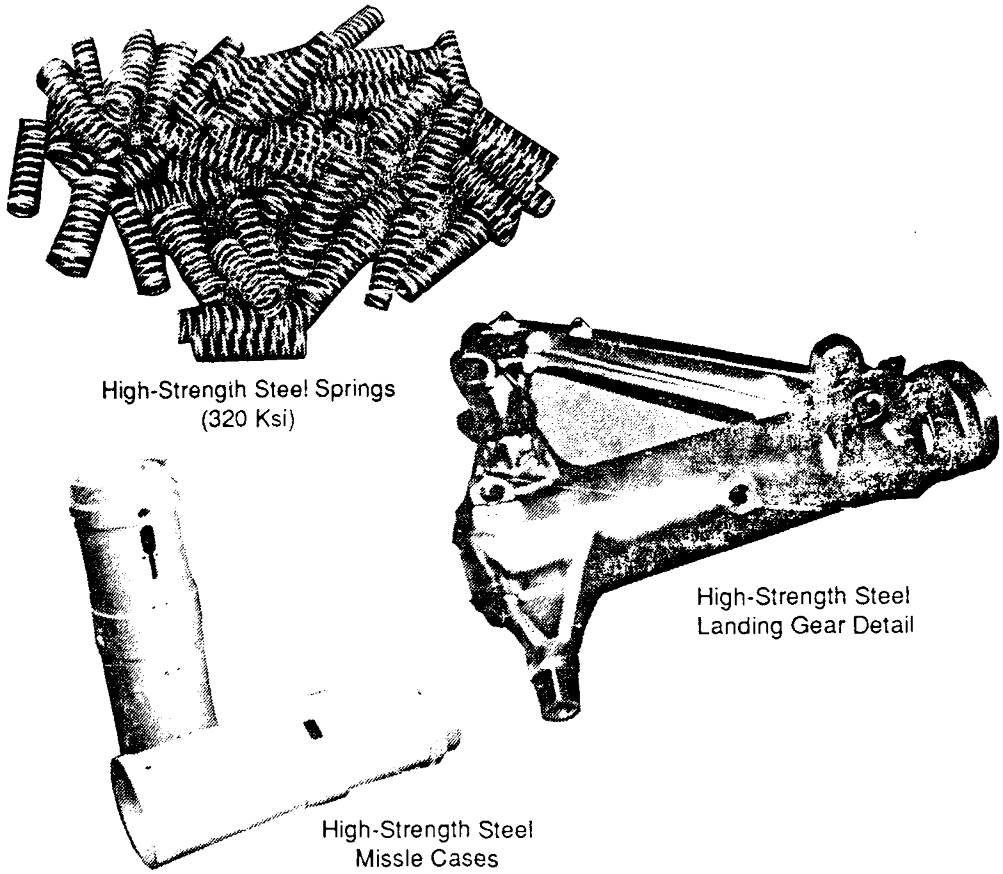


Figure 27. Typical IVD Aluminum-Coated High-Strength Steel Details.

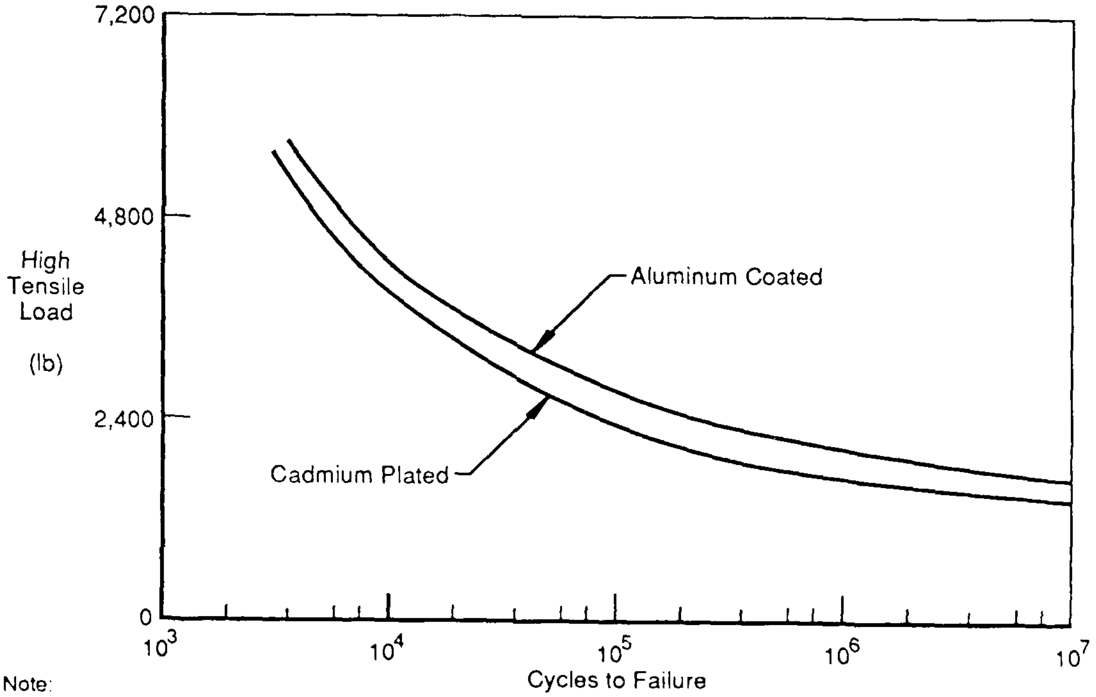
the military specification, MIL-C-83488, requires that the composition of both the 1100 alloy aluminum wire evaporant and the as-deposited coating be a minimum of 99 percent pure aluminum. An examination of the wire and coating using an energy dispersion x-ray technique showed only the element aluminum (Reference 59). A sampling of the testing conducted to verify that the IVD aluminum process has no adverse effect on fatigue properties is presented in Table 18.

TABLE 18. EFFECT OF IVD ALUMINUM COATING ON SUBSTRATE FATIGUE PROPERTIES.

Company	Substrate	Fatigue Test	Effect on Fatigue[a]
Pratt & Whitney (Reference 27 and 36)	8-1-1-Titanium 6-4-Titanium 410 Steel	High Cycle High Cycle Peak Strain	None None Slight – Same as Nickel-Cadmium
Westinghouse (Reference 28)	A276 Steel A276 Steel 403 Stainless Steel	20 KHz 20 KHz 20 KHz	None
SPS Technologies (Reference 32)	Steel	Tension-Tension	Slight – Same as "Bright" Cadmium
McDonnell Douglas (Reference 60)	2024 Aluminum Alloy	6 g Symmetric	None
Turbine Support (Reference 62)	Steel	High Cycle	None

a "None" – Less than 3 percent reduction
"Slight" – Less than 5 percent reduction

As with IVD aluminum, the various cadmium processes produce a soft, ductile finish and have little or no effect on fatigue properties. Figure 28 shows fatigue data for IVD aluminum and electroplated cadmium on alloy steel



Note:
1. Twelve NAS 1954 alloy steel fasteners were used.
2. The test method was MIL-STD-1312, test no. 11.

Figure 28. Tension Fatigue Test of IVD Aluminum- and Cadmium-Finished Fasteners.

fasteners from tests conducted by MCAIR (Reference 62). Similar data is presented in Table 19 from tests conducted by SPS Technologies (Reference 32). In a third comparison, Table 20 shows IVD aluminum and diffused nickel

TABLE 19. TENSION-TENSION FATIGUE TEST OF IVD ALUMINUM- AND CADMIUM-FINISHED FASTENERS.

Bolt Description[a] and Test Loads	Cycles to Failure[b]		
	Bare	IVD	Cadmium
MS21250-04-018 Per MIL-B-8831	135.400	173.000	83.000
Alloy Steel	102.000	109.400	114.000
(Maximum Load – 3.210 lb.	72.200	107.700	125.000
Minimum Load – 321 lb)	118.800	90.400	128.000
	178.600	102.100	123.000
Average	121.500	116.520	114.600

a NAS 1271-16 alloy steel fasteners
b Test method - MIL-STD-1312 test no. 1 - speed 8.000 cycles per min

cadmium (amoung 25 finishes tested) ranked first and second, respectively, for having the least effect on fatigue properties of alloy steel turbine blades. Table 20 was taken from a Westinghouse Electric report (Reference 28).

TABLE 20. EFFECT ON FATIGUE PROPERTIES OF ALLOY STEEL STEAM TURBINE BLADES.

Coating System	Ranking From the Salt-Spray Test	Ranking From the 20 kHz Fatigue Test (Decreasing Endurance Values)	Combined Rank (Equal Weight)
Aluminum, Wire Gun	18	16	19
Aluminum, Pack Cementation	7	8	6
Aluminum-Nickel, Pack Cementation	5	3	3
Aluminum, Ion-Vapor-Deposition	1	1	1
Zinc-Silicate Binder (Inorganic Zinc Paint)	3	18	10
Nickel-Cadmium, Electroplate	2	2	2
Aluminum-Phosphate Binder (Spray and Bake)	4	18	12
Nickel-Aluminide High Energy Plasma Spray	13	7	9
Chromium, Chromate Conversion	16	6	11
Chromium, Diffusion (Chromizing)	12	13	14
Zirconium, Physical Vapor Deposition	19	14	18
Nickel-Chromium, Conventional Plasma Spray	17	9	15
Chromium Boride, Pack Cementation	14	17	17
Iron-Chromium Boride, Pack Cementation	15	12	16
Silicon Diamine	11	4	5
PTFE Powder	6	5	4
Nickel, Chemical Vapor Deposition	8	10	7
Sulfamate-Nickel, Electroplate (Thin Coating)	10	14	13
Sulfamate-Nickel, Electroplate (Thick Coating)	9	11	8

In summary, testing has verified that IVD aluminum coatings have no effect on the fatigue or other mechanical properties of the base metal. In addition, after more than a decade of production use, there have been no field reports of mechanical property degradation or resulting part failure.

SECTION V

FASTENER INSTALLATION CHARACTERISTICS

A. TORQUE-TENSION

Aluminum has a higher coefficient of friction than cadmium. Therefore, a higher torque is required to install aluminum coated fasteners to a given tension preload than if the fastener was cadmium plated. The use of a lubricant on the aluminum-coated fastener and/or nut, however, eliminates or greatly reduces torque-tension differences. This section compares torque-tension values for IVD aluminum, cadmium, and diffused nickel-cadmium finished fasteners with and without the use of supplemental lubricants.

Figure 29 shows the results of a torque-tension test conducted by SPS Technologies (Reference 32). The torque on the alloy-steel locknuts is shown versus the average induced tension load on the H-11 bolts used in the tests.

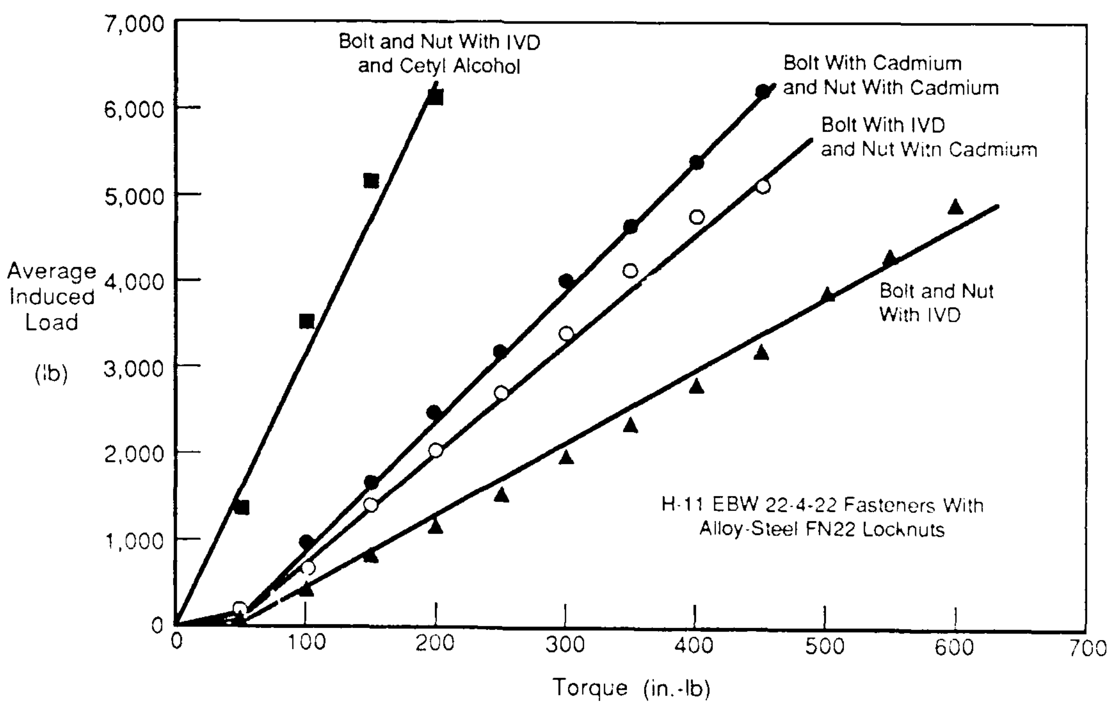


Figure 29. Torque-Tension Test Results for IVD Aluminum- and Cadmium-Finished Fasteners.

When both the bolt and nut were coated with IVD aluminum, approximately 60 percent more torque was needed to produce a 2000-pound tension load than when both were cadmium-plated. Using a cadmium-plated nut with the IVD aluminum-coated bolt reduced the difference to approximately 15 percent. When the IVD-coated nuts and bolts were lubricated with cetyl alcohol, the torque for a given induced tension load was actually 70 percent less than if the nut and bolt were cadmium-plated. In this test, therefore, the effect of the lower lubricity of the IVD aluminum coating was more than offset by the addition of a lubricant.

MCAIR compiled data from two series of torque-tension tests (Reference 63) conducted during formal qualification of IVD aluminum as an acceptable alternative to cadmium. In the first series of tests, the initial torque required to develop a 1200-pound tension load in 3/16 inch diameter nonlubricated, IVD aluminum-coated or cadmium-plated bolts was measured for various nut configurations. The relative torque differences, based on an average of 8 tests for each condition, are as follows:

- An 8 percent higher torque was required using IVD aluminum versus cadmium when the torque was applied to cadmium plated, nonlocking, nonlubricated nuts.

- An 8 percent higher torque was required using IVD aluminum versus cadmium when the torque was applied to cadmium plated, dry-film-lubricated, self-locking nuts.

- The same torque was required using IVD aluminum- and cadmium-finished bolts when the torque was applied to the bolts with cadmium-plated, dry-film-lubricated, self-locking nuts.

- A 36 percent higher torque was required using IVD aluminum versus cadmium when the torque was applied to the bolts with cadmium-plated, dry-film-lubricated, self-locking gang channel nuts.

In the second series of tests, the initial torque required to induce a specific tension load in 3/16-inch diameter, IVD aluminum-coated or cadmium-plated bolts was measured. Some of the bolts were lubricated and the torque was applied to cadmium-plated, dry-film-lubricated, self-locking nuts. The test results are as follows:

o A 10 percent higher torque was required using IVD aluminum versus cadmium to attain a 560 pound load in a nonlubricated bolt.

o An 8 percent higher torque was required using IVD aluminum versus cadmium to attain a 560-pound load in a lubricated bolt.

o The torques required using IVD aluminum and cadmium finishes were approximately the same to attain a 2000-pound load in a lubricated bolt.

Boeing conducted torque-tension tests comparing IVD aluminum and diffused nickel-cadmium on nonlubricated H-11 steel bolts (Reference 37). Figures 30

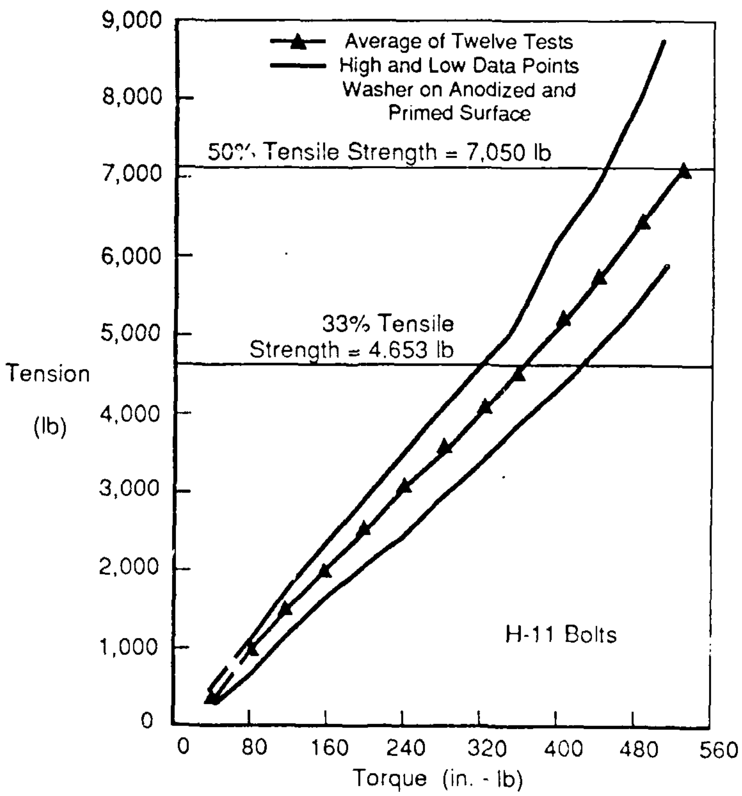


Figure 30. Torque-Tension Relationship Using IVD Aluminum-Finished Fasteners.

and 31 show the torque-tension curves produced using the IVD aluminum finish were nearly identical to those produced using diffused nickel-cadmium.

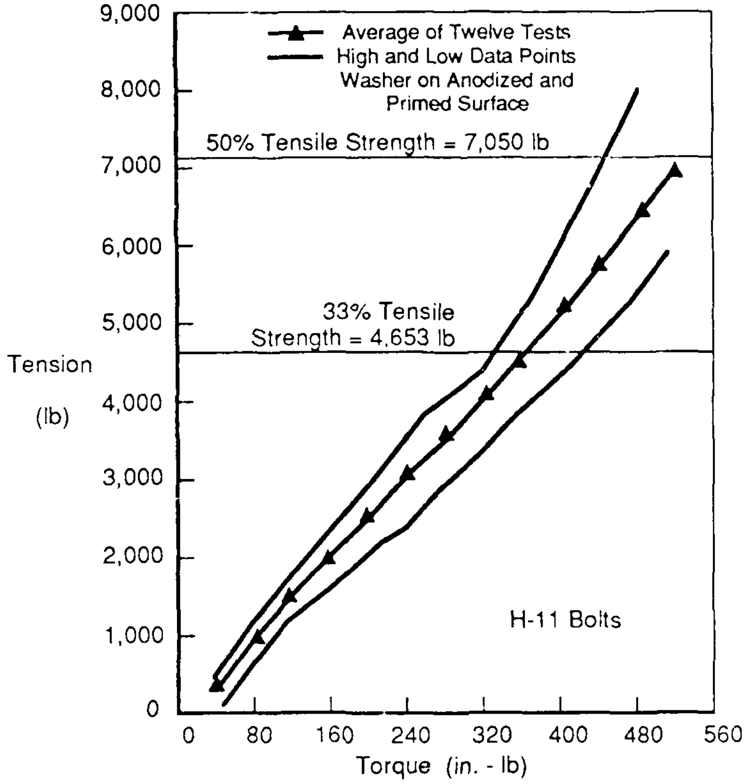


Figure 31. Torque-Tension Relationship Using Diffused Nickel-Cadmium-Finished Fasteners.

The Hi-Shear Company also evaluated torque-tension using IVD aluminum and diffused nickel-cadmium on lubricated H-11 pin and collar type fasteners (Reference 64). They reported that torque-tension was essentially unaffected by any differences in the two finishes (Tables 21 and 22).

In contrast however, Pratt & Whitney reported that a considerably higher torque was required with IVD aluminum in comparison to diffused nickel-cadmium (Reference [illegible]). Axial load versus applied torque for [illegible] bolts ([illegible]), finished with IVD aluminum and diffused nickel-cadmium was evaluated. The effect of engine oil on the bolts was also measured since it was common practice to dip the bolt in oil before assembly. In all cases, the IVD aluminum-finished bolts required a higher torque to produce the same axial load than did the diffused nickel-cadmium-finished bolts. For example, the

TABLE 21. TORQUE-TENSION VALUES USING IVD ALUMINUM- AND DIFFUSED NICKEL-CADMIUM-FINISHED FASTENERS.

Sample No.	IVD + Cetyl HL117-8-16 Pins With HL70 Collars		Diffused Ni-Cd + Cetyl HL117-8-16 Pins With HL70 Collars	
	Torque-Off (in.-lb)	Preload (lb)	Torque-Off (in.-lb)	Preload (lb)
1	69	2,700	67	2,225
2	71	2,700	73	2,650
3	68	2,500	71	2,400
4	68	2,500	68	2,250
5	67	2,500	69	2,550
Mean	68.6	2,600	69.6	2,415
Standard Deviation	1.5	100	2.4	185
Required	60 – 80	1,600	60 – 80	1,600

TABLE 22. TORQUE-TENSION VALUES USING IVD ALUMINUM- AND DIFFUSED NICKEL-CADMIUM-FINISHED FASTENERS.

Sample No.	IVD + Cetyl HL117-8-16 Pins With HL86 Collars		Diffused Ni-Cd + Cetyl HL117-8-16 Pins With HL86 Collars	
	Torque-Off (in.-lb)	Preload (lb)	Torque-Off (in.-lb)	Preload (lb)
1	120	3,900	111	3,825
2	118	3,450	124	4,400
3	120	3,650	116	3,850
4	121	3,500	120	4,050
5	123	3,725	118	4,200
Mean	120.4	3,645	117.8	4,065
Standard Deviation	1.8	180	4.8	242
Required	115 – 130	2,600	115 – 130	2,600

In the Pratt & Whitney tests, coating thickness is the probable cause for the considerably higher torque required using IVD aluminum. Most fasteners threads are designed to accept 0.0003-0.0005 inches of coating. This is the normal Class 3 thickness range for IVD aluminum finished fasteners. However, Pratt & Whitney reported the test fasteners were finished with Class 2 (0.0005-inch minimum) IVD aluminum.

Table 23 summarizes the changes to torque-tension relationships when using IVD aluminum versus cadmium and nickel-cadmium finishes. Because of the scatter in the test data and the variation in parameters for the different tests, Table 23 should be used only as a rough guide as to what might be expected. It is clear from the data reviewed, however, that the higher

TABLE 23. TORQUE-TENSION RELATIONSHIP USING IVD ALUMINUM VERSUS CADMIUM AND DIFFUSED NICKEL-CADMIUM FINISHES.

Component Torqued – Finish	Changes in Torque Using IVD Aluminum	
	vs Cadmium	vs Nickel-Cadmium
Locknut – Bolt and Nut IVD Coated With No Lubrication	+60%	No Change
Locknut – Bolt and Nut IVD Coated and Lubricated	–70%	
Locknut – IVD Coated Bolt With Cadmium Plated Nut and No Lubrication	+15%	
Locknut – IVD Coated Bolt With Cadmium Plated and Lubricated Nut	+9%	
Locknut – Lubricated, IVD Coated Bolt With Cadmium Plated and Lubricated Nut	+4%	
Locknut – Lubricated IVD Coated Bolt With Cadmium Plated and Lubricated Locknut	+4%	
Non-Locking Nut – IVD Coated Bolt With Cadmium Plated Nut and No Lubrication	+8%	
Bolt – Bolt and Nut IVD Coated With No Lubrication		+140%
Bolt – IVD Coated Bolt With Cadmium Plated and Lubricated Locknut	+18%	
Collar – Pin and Collar IVD Coated and Lubricated		No Change

coefficient of friction of IVD aluminum increases the torque required for a given preload; it is also clear that lubrication reduces or eliminates this increase.

A review of production operations involving the use of IVD aluminum as a replacement for cadmium on fasteners verifies the relative ease that such a changeover can be accomplished for most applications. Some of these operations have been ongoing for the past 12 years. For the most part, they have been accomplished with no more than the use of a lubricant and without significant changes to installation procedures, tools, or hole sizes.

Although IVD aluminum has been successfully used on millions of aerospace fasteners, torque-tension relationships are a legitimate concern for some applications. MCAIR has proposed a research and development program, described in Section XII(C), to demonstrate that acceptable results can be obtained with the selection of a proper lubricant.

B. REUSE TESTING

Service doors and panels on aircraft are usually secured with removable type fasteners and locknuts. The fastening system is required to meet reuse standards to accommodate periodic door or panel removal and reinstallation. Acceptability limits are set in accordance with MIL-N-25027 which establishes maximum locking and minimum breakaway torques over a number of installation cycles. This section presents data generated by MCAIR and SPS Technologies on the reuse characteristics of IVD aluminum and electroplated cadmium finished fastening systems.

SPS ran a 15 cycle reuse test on 1/4 inch diameter fasteners (Reference 32). Each cycle involved tightening a nut onto a bolt with 100 inch-pounds of torque, then removing the nut. Neither the nut nor the bolt were lubricated. MIL-N-25027 establishes a maximum locking torque of 30 inch-pounds and a minimum breakaway torque of 3.5 inch-pounds. With no lubrication, initial locking torques for both aluminum- and cadmium-finished hardware were over the maximum. Table 24 shows that the IVD aluminum-coated

TABLE 24. REUSE TEST RESULTS COMPARING IVD ALUMINUM- AND CADMIUM-FINISHED FASTENERS.

Finish		Average[a] Torque (in.-lb)											
		Cycle 1		Cycle 3		Cycle 6		Cycle 9		Cycle 12		Cycle 15	
Nut	Fastener	Maximum Locking	Minimum Breakaway	Maximum Locking	Minimum Breakaway	Maximum Locking	Minimum Breakaway	Maximum Locking	Minimum Breakaway	Maximum Locking	Minimum Breakaway	Maximum Locking	Minimum Breakaway
					Designations	Nut - 42FIW	Fastener - MS21250-04-018						
Cadmium	IVD Aluminum	60	50	46	42	30	34	26	26	26	[illegible]	[illegible]	[illegible]
IVD Aluminum	IVD Aluminum	56	52	28	28	21	22	21	21	25[b]	24[b]	[illegible]	[illegible]
Cadmium	Cadmium	42	38	37	36	24	26	24	24	21	21	[illegible]	[illegible]
					Designations	Nut - FN22	Fastener - EWB 22-4-21						
IVD Aluminum	IVD Aluminum	56	55	30	31	21	21	19	19	19	[illegible]	15	[illegible]

a. This was an average of two results per condition.
b. One result only, the nut seized after the [illegible] cycle on the second test.

nut-and-bolt combinations had higher torque values for the initial installation cycle than the cadmium-plated nut-and-bolt combinations; torque values were much closer for subsequent cycles. Figure 32 shows that as the number of installation cycles increases, the drop-off in maximum locking torque using IVD aluminum-coated fastening systems is similar to the drop-off using cadmium plating.

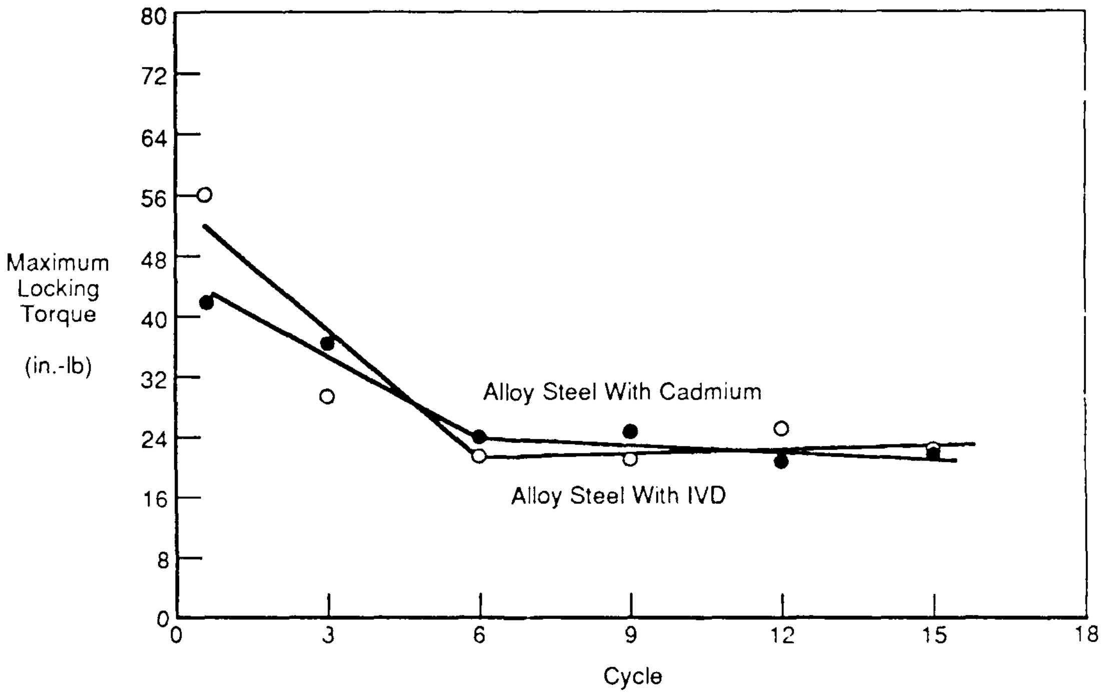
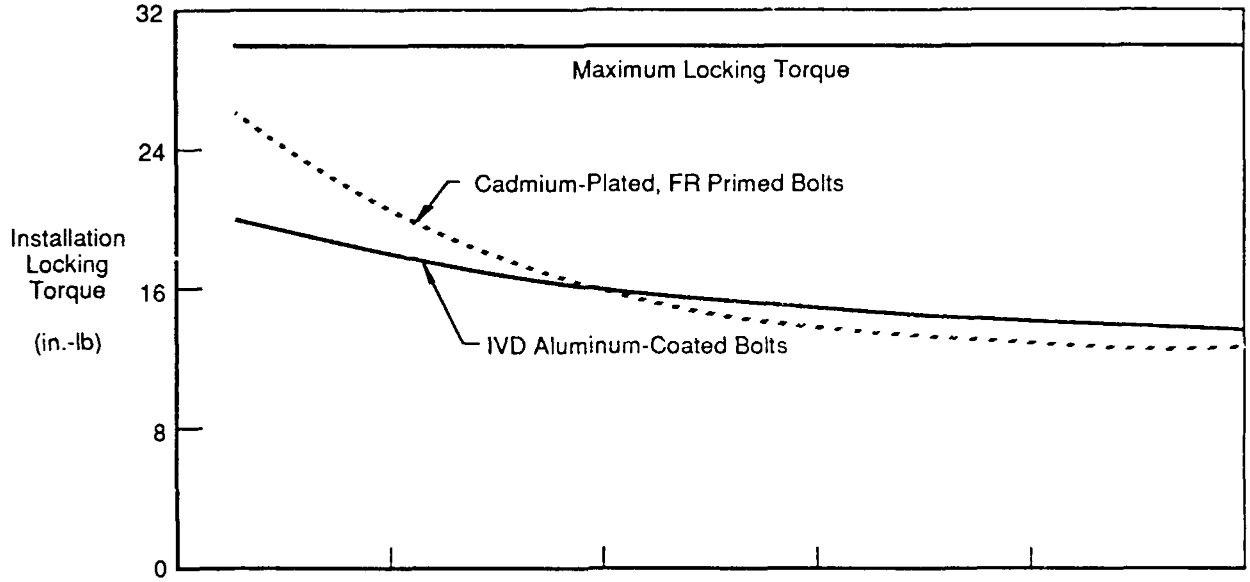


Figure 32. Reuse Relationships for IVD Aluminum- and Cadmium-Finished Fasteners.

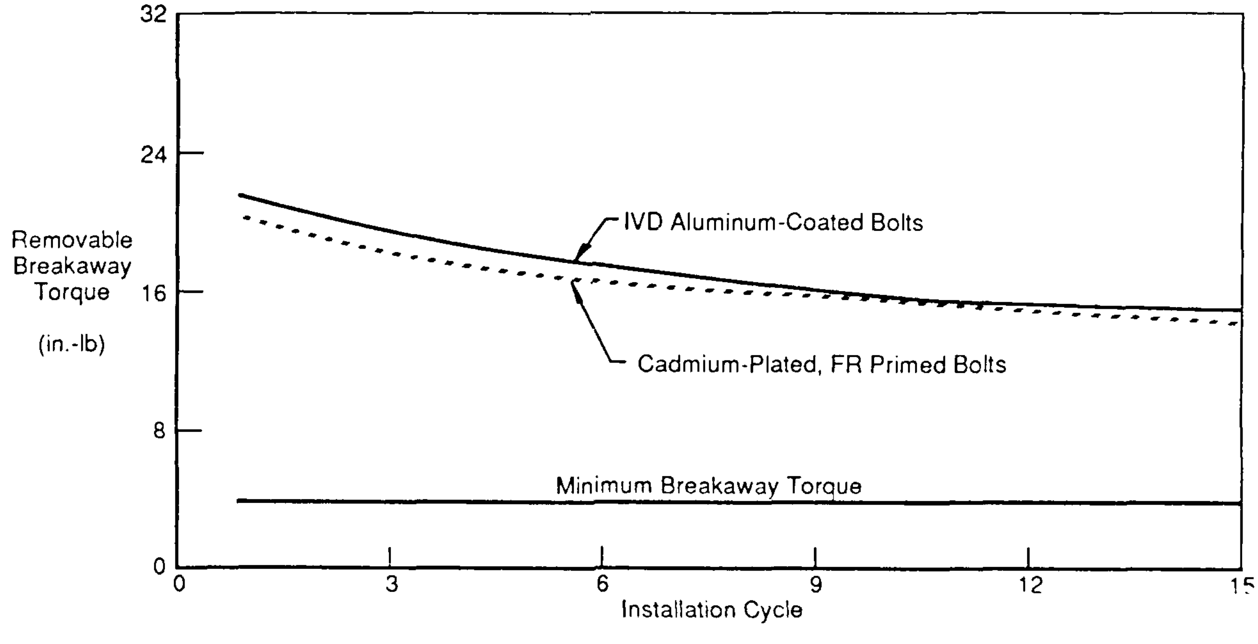
MCAIR also conducted a 15-cycle reuse test during formal qualification of IVD aluminum as an acceptable alternative to cadmium (Reference 63). The reuse test compared 1/4-inch diameter IVD aluminum-coated and cadmium-plated alloy steel bolts installed into cadmium-plated alloy steel gang channels and locknuts. The locknuts were lubricated with molybdenum disulfide and attached to typical aircraft substructure to simulate removable door installations. MCAIR tested an IVD aluminum-coated bolt and a cadmium-plated nut combination because aluminum on the bolts provides better corrosion resistance, especially for moldline applications, and better compatibility to the aircraft structure; see discussion in Section III(C). The cadmium-plated locknuts are of little concern from a corrosion or compatibility standpoint. Since cadmium-plated fasteners used on the aircraft were painted with fluid resistant (FR) primer on the fastener heads and shanks for additional corrosion protection, similarly finished fasteners were used in the tests. The IVD aluminum-coated fasteners were not painted. Each cycle involved installing the fastener into the nut, torquing the fastener to 50 inch-pounds, and removing the fastener. About half the fasteners were installed using hand torque wrenches, and the remaining fasteners were installed with controlled-torque power screwdrivers. Figure 33 shows that both finishes were within the limits of MIL-N-25027.

By using lubricants, reuse characteristics can be improved, and the effect caused by differences in finishes can be minimized. This is demonstrated by comparing the initial locking torques in the SPS test in which no lubricants were used to those in the MCAIR test in which the locknuts were lubricated. For example, the first installation cycle in the SPS test for the combination of aluminum-coated fasteners and cadmium-plated locknuts required a locking torque of [illegible] inch-pounds versus 20 inch-pounds in the MCAIR test. The military specification maximum is 30 inch-pounds. This limit was also exceeded in the SPS test by the cadmium - cadmium combination (42 inch-pounds) without a lubricant.

Table 25 summarizes reuse characteristics of fastening systems with different finish combinations compared to the limits established in MIL-N-25027. Reuse characteristics of IVD aluminum-coated bolts with



Notes :1. Fastener : NAS584-8 flush head bolt, alloy steel, IVD aluminum, or
3MFR584-8 flush head bolt, alloy steel, cadmium plated, FR primed.
Nut : 3M143A4-2 plate nuts or 3M150N4-8-10 gang channel.
2. Maximum locking torque per MIL-N-25027 for 1/4 in. diameter fasteners.
3. Torque applied to fastener by hand torque wrench or power screwdriver.
4. Fastener tightened to 50 in.-lb each cycle.
5. Data shown is average of 20 tests.



Notes :1 Fastener : NAS584-8 flush head bolt, alloy steel, IVD aluminum, or
3MFR584-3 flush head bolt, alloy steel, cadmium plated, FR primed.
Nut : 3M143A4-2 plate nuts or 3M150N4-8-10 gang channel.
2. Minimum breakaway torque per MIL-N-25027 for 1/4 in. diameter fasteners.
3. Torque applied to fastener by hand torque wrench or power screwdriver.
4. Fastener tightened to 50 in.-lb each cycle.
5. Data shown is average of 36 to 40 tests.

Figure 33. Fifteen Cycle Reuse Test Comparing IVD Aluminum- and Cadmium-Finished Fasteners.

TABLE 25. REUSE CHARACTERISTICS COMPARED TO SPECIFICATION LIMITS.

Fastening System		Reuse Characteristics			
		1st Cycle		15th Cycle	
Finish Combination (Nut-Bolt)	Lubrication	Locking Torque	Breakaway Torque	Locking Torque	Breakaway Torque
Cd-Cd	No	+	✓	+	✓
Cd-Al	No	+	✓	✓	✓
Al-Al	No.	+	✓	✓*	✓*
Cd-Cd	Yes	✓	✓	✓	✓
Cd-Al	Yes	✓	✓	✓	✓

Key:
+ - Exceeded MIL-N-25027E limits
✓ - Within MIL-N-25027E limits
* - Within limits on 2/3 samples

lubricated locknuts fall within the limits. The program proposed by NCAIR to broaden the data base for acceptable lubricants relevant to torque-tension characteristics, discussed in Section XII(C), will also provide useful information about reuse characteristics.

SECTION VI

COATING VERSATILITY

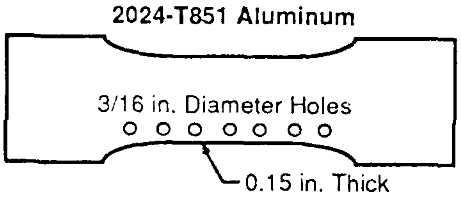
A. ALUMINUM ALLOY SUBSTRATES

IVD aluminum coatings are easily applied to all metallic substrates including aluminum alloys. Electroplated cadmium, on the other hand, can not be applied directly to aluminum alloy substrates with acceptable adhesion. MCAIR began applying IVD aluminum coatings to aluminum alloy production parts in 1976. Initially, IVD coatings replaced anodize coatings on fatigue critical aluminum structure. In more recent applications, they replace electroplated tin on aluminum alloy components requiring a conductive path as well as corrosion resistance. The pure IVD aluminum coating is ideally compatible with aluminum alloy structure. It is less noble than the alloys and therefore provides sacrificial corrosion resistance. Currently, more than 800 aluminum alloy parts are coated on three MCAIR production aircraft. In all applications, the IVD coating has improved performance and reduced either processing costs or life cycle costs, or both. Of the thousands of aircraft parts coated and more than a decade of in-service aircraft exposure, no problems have been reported.

1. Fatigue Critical

The soft ductile IVD aluminum is used on fatigue critical aluminum alloy structure; it provides excellent sacrificial corrosion resistance and does not reduce fatigue properties. Hard, brittle finishes, however, can affect the mechanical properties of the base metal. MCAIR tests (Reference 60) showed fatigue reductions of 30 percent or more with the use of anodize on a 2024-T651 aluminum alloy test specimen (Figure 34). On existing structures, the use of IVD aluminum can extend fatigue life and eliminate the need for fatigue enhancement, such as shot peening, and thereby reduce costs. For new designs, the higher fatigue properties achieved through the use of IVD aluminum allow for a less beefy structure; this saves weight. In addition,

Surface Finish	Type of Fastener	Fatigue Life (hr)	Average Fatigue Life (hr)
Bare	Taper-Loks	59,544 63,129	61,300
Anodize	Taper-Loks	29,704 31,126	30,400
Peen and Anodize	Taper-Loks	45,700 43,700	44,500
IVD	Taper-Loks	59,129	59,100
Peen and IVD	Taper-Loks	40,225 61,129 97,205	66,200



Note:
Specimens tested to spectrum developed from flight test strain gage data with 6g symmetric fatigue stress = 24.3 ksi gross section.

GP83-0398-7

Figure 34. Effect on Fatigue Properties by IVD Aluminum and Anodize Finishes.

IVD aluminum improves the resistance to stress corrosion cracking. Typical high-strength, aluminum alloy structural parts coated with IVD aluminum are shown in Figures 35 and 36.

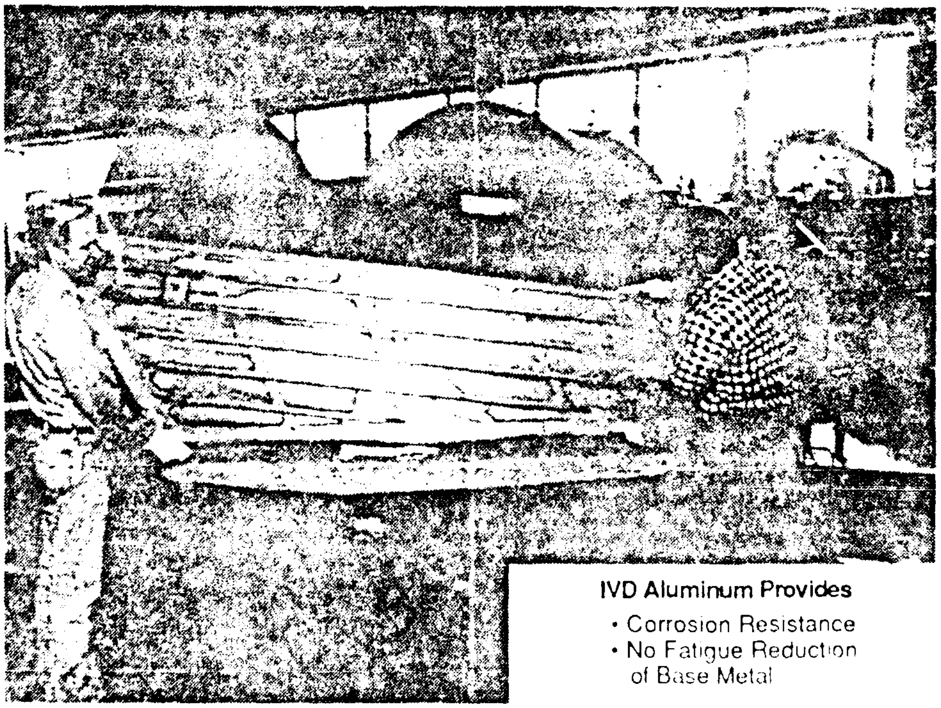


Figure 35. F-15 Aluminum-Coated Fatigue-Critical Aluminum Alloy Wing Skin.

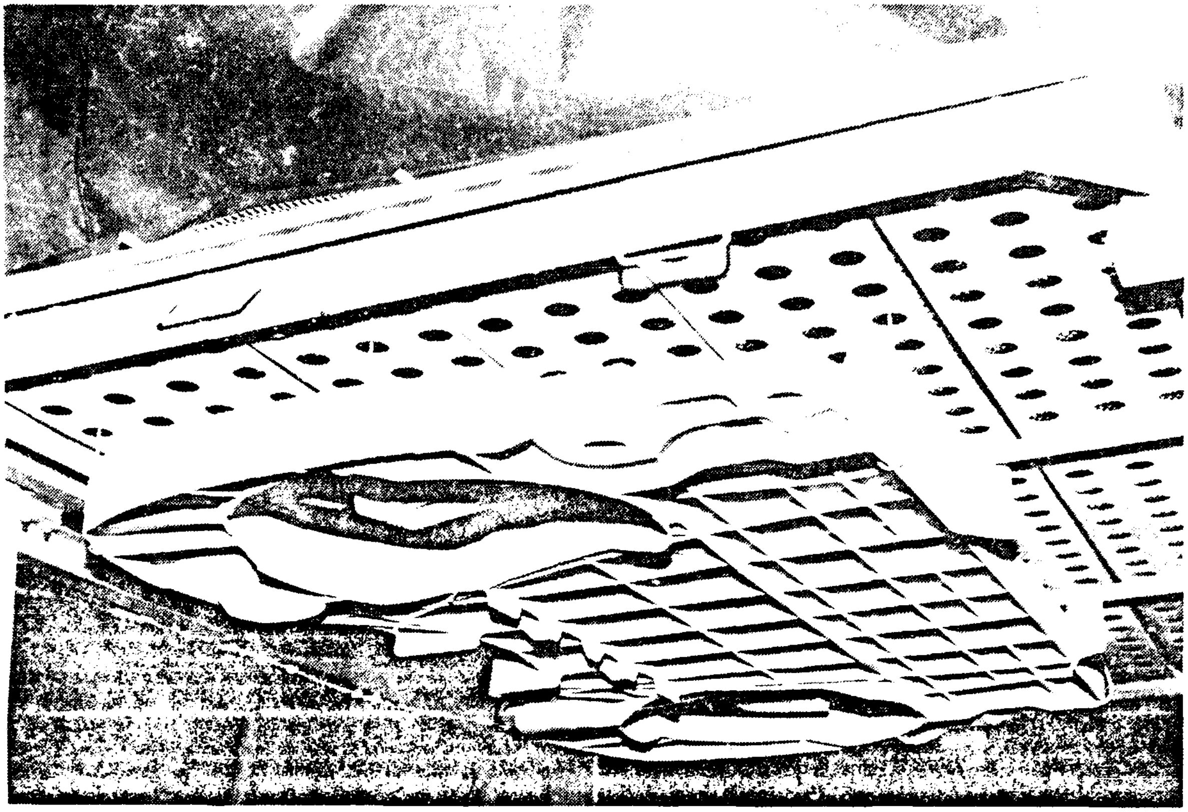


Figure 36. F-18 IVD Aluminum-Coated Fatigue-Critical Aluminum Alloy Bulkhead.

2. Electrical Bonding/EMIC

Many aluminum alloy components such as fuel and pneumatic line fittings, shown in Figure 37, require a conductive path across joints to dissipate static electrical charges generated by fluid or air flow. Typically, these components are anodized making them nonconductive. Therefore, an electrical bonding strap or jumper is required to establish the conductive path. IVD aluminum is highly conductive and remains so in service when treated with a standard chromate conversation coating; electrical properties are discussed in Section II(E). IVD aluminum, instead of anodizing, on the fittings provides corrosion resistance and an inherent electrical bond across the joint interface. The weight penalty is eliminated, and substantial costs are saved by eliminating the labor-intensive step of installing the bonding strap (Figure 38).

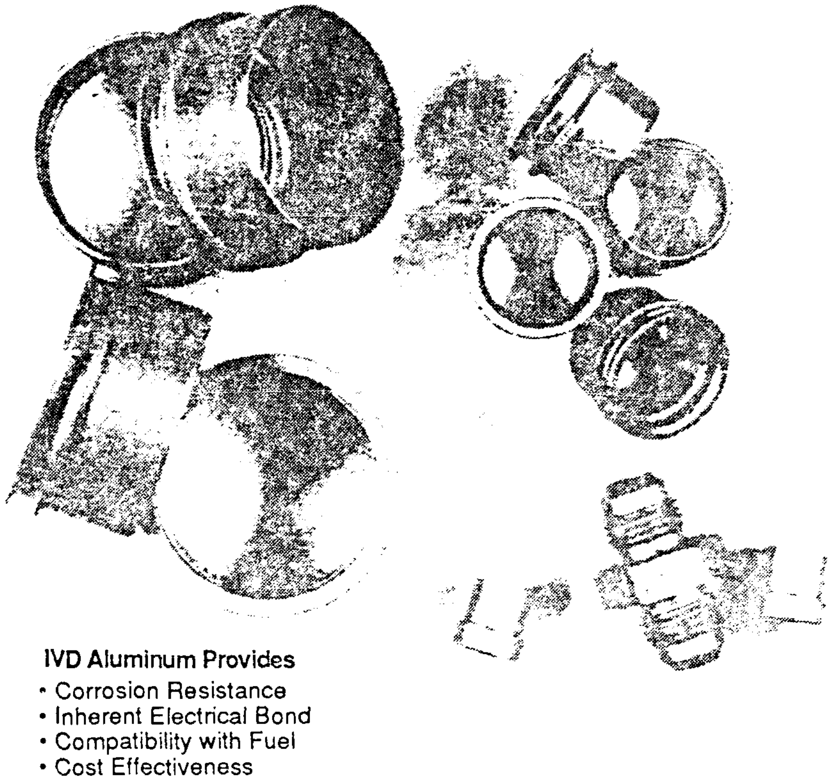


Figure 37. IVD Aluminum-Coated Aluminum Alloy Fuel and Pneumatic Line Fittings.

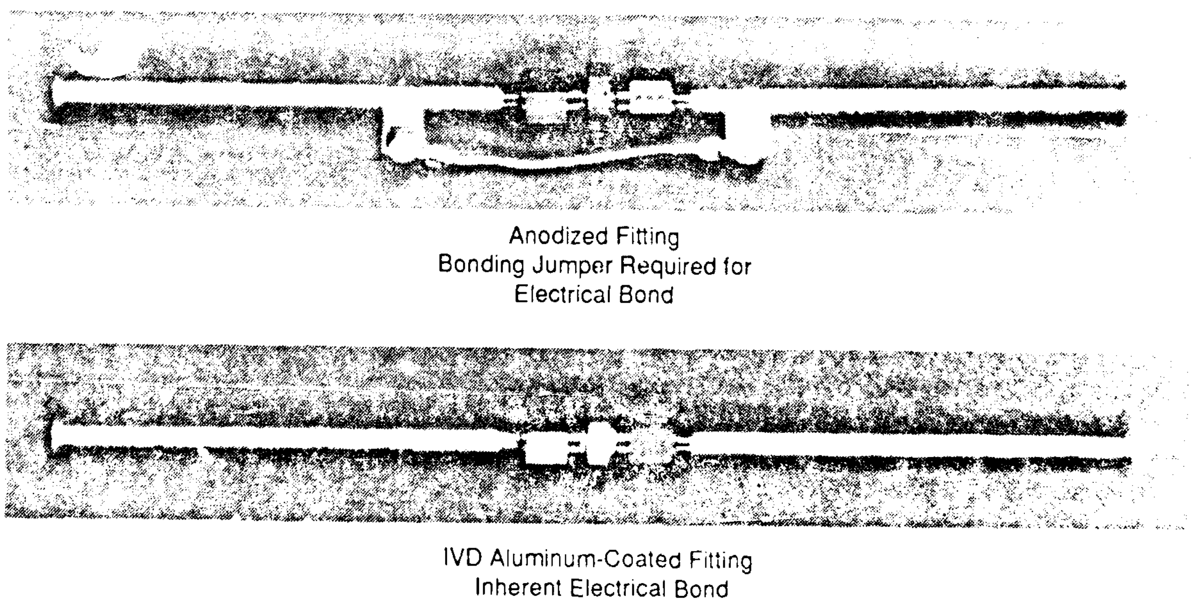


Figure 38. IVD Aluminum-Provided Conductive Path and Corrosion Resistance.

Electroplated tin is sometimes used on aluminum alloy components to provide a low-resistance, conductive path at the interface with other components for electromagnetic interference compatibility (EMIC). However, it is difficult to achieve good adhesion of the tin to the aluminum alloy. Also, tests have shown that the tin provides relatively poor protection of the substrate in a corrosive environment (References 67 and 68); corrosion causes the electrical resistance to increase. IVD aluminum offers far superior corrosion resistance. The aluminum coating is sacrificial to the substrate, whereas tin is more noble. Tables 26 and 27 show that IVD aluminum-coated details have a much lower joint resistance after exposure to corrosive environments than tin-plated details. In this application, IVD aluminum offers higher performance, reduced processing problems, and lower maintenance costs.

TABLE 26. IVD ALUMINUM VERSUS ELECTROPLATED TIN FOR EMIC – ST. LOUIS OUTDOOR EXPOSURE.

Test Condition	Joint Electrical Resistance (milliohms)	
	Electroplated Tin	IVD Aluminum
Typical Resistance Before Exposure	Less Than 1	Less Than 1
Resistance After 2 Years	800	22
Resistance After 3 Years	*	1
Resistance After 4 Years	*	2
Resistance After 5 Years	*	2

Key
*Too corroded to test

TABLE 27. IVD ALUMINUM VERSUS ELECTROPLATED TIN FOR EMIC - 1 YEAR SHIPBOARD EXPOSURE (USS CONSTELLATION).

EMIC Assemblies			
Specimen Number	Resistance Measurements (milliohms)		
	Interfacing Coatings	Resistance Before Exposure	Resistance After Exposure
A-1 (1) A-1 (2)	Alclad to Alclad	0.12 - 0.13	0.35 2.82 - 2.85
A-2 (1) A-2 (2)	Tin to Alclad	0.07 - 0.09	195.000 - 196.000 520 - 540
A-3 (1) A-3 (2)	IVD Al to Alclad	0.45 - 0.78 0.22 - 0.54	0.82 - 0.84 6.10 - 6.13
B-1 (1) B-1 (2)	Tin to IVD Al	0.22 - 0.62	2.0 - 2.1 199.000 - 200.000
B-2 (1) B-2 (2)	IVD Al to IVD Al	0.25 - 1.3	0.32 4.9
B-3 (1) B-3 (2)	Tin to Tin	0.03 - 0.05	200.000

Figure 39 shows an aluminum alloy casting coated with IVD aluminum, masked along areas required to be electrically conductive for EMIC, then black-anodized to meet cockpit color requirements. Whereas IVD aluminum is not normally anodized, it can be when applied to aluminum alloy substrates. This application shows the versatility of the IVD coating.

5. Electrical Connectors

IVD aluminum has a distinct advantage over cadmium and nickel on aluminum alloy connectors. To meet adhesion requirements, cadmium must be electroplated over a copper or nickel strike. Nickel plating is used for high temperature applications. IVD aluminum can replace both the cadmium plating (with strike) and the nickel plating. Nickel by itself and the combination of cadmium with copper or nickel are both more noble than the aluminum alloy connector shell. They do not provide sacrificial corrosion resistance, and pits in the connector shells are common in corrosive environments. In tests conducted by MCAIR (references 69 and 70), IVD aluminum provides the needed electrical conductivity, in addition to corrosion protection, that would allow the 500-hour salt-spray requirements of common connector specifications like

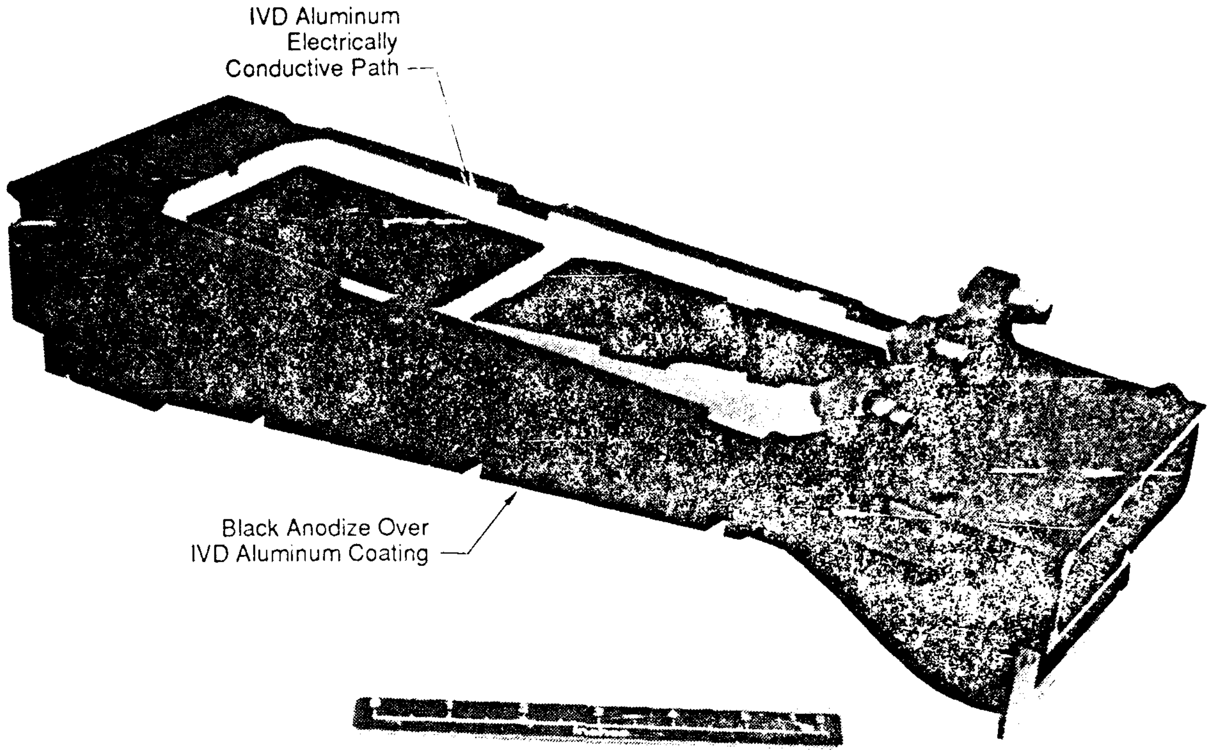


Figure 39. Aluminum Alloy Casting Coated With IVD Aluminum and Black Anodized.

MIL-C-38999 to be increased to 1,000 hours (Figure 40). The connectors shown in Figure 40 were also mated and unmated 150 times per MIL-C-38999 -- 50 times each before exposure, after 500 hours of exposure, and after 1,000 hours of exposure. Nickel plated connectors cannot normally be unmated due to corrosion after 500 hours of exposure.

B. TITANIUM SUBSTRATES

IVD aluminum coatings are easily applied to titanium alloy substrates. They are most often used to provide galvanic compatibility with aluminum alloy structure and/or provide improved electrical conductivity. MIL-STD-1568 prohibits the use of cadmium, either on or in direct contact with titanium because of the possibility of solid metal embrittlement.

An example of the use of IVD aluminum for galvanic compatibility is on titanium fasteners. Whereas the fasteners do not corrode, they are galvanically more noble than the aluminum alloy structure in which they are

Figure 40. IVD Aluminum- and Cadmium-Finished Connectors After 1,000 Hours of Neutral Salt Fog Exposure.

installed. Consequently in a corrosive environment, a galvanic cell will form between the aluminum alloy structure and bare titanium fastener. Structural pitting or corrosion of the aluminum will result. These same fasteners when coated with IVD aluminum are galvanically compatible with the aluminum alloy structure. Sometimes paint and sealant are used on bare titanium fasteners to form a "barrier" between the two dissimilar metals. However, as demonstrated in tests conducted by MCAIR (References 71 and 72), the "barrier" coatings were not as effective as IVD aluminum in protecting the aluminum structure. Figure 41 shows both IVD aluminum-coated and sealant-coated (wet-installed) titanium fasteners in a 7075-T6 aluminum alloy block. The fastener and block assembly was painted, then installed in a corrosive SO_2 salt fog environment. After 28 days of exposure, the alloy aluminum block was sectioned at the countersinks. The photomicrographs in Figure 42 provide a comparison of the protection given to the countersinks and shows the obvious superiority of IVD aluminum.

Another advantage of IVD aluminum coatings compared to "barrier" type coatings on titanium fasteners is that the aluminum coating is electrically conductive. In contrast, the barrier coatings form an electrical insulator. Some users of IVD aluminum on titanium fasteners require a conductive coating to help disperse lightning strikes.

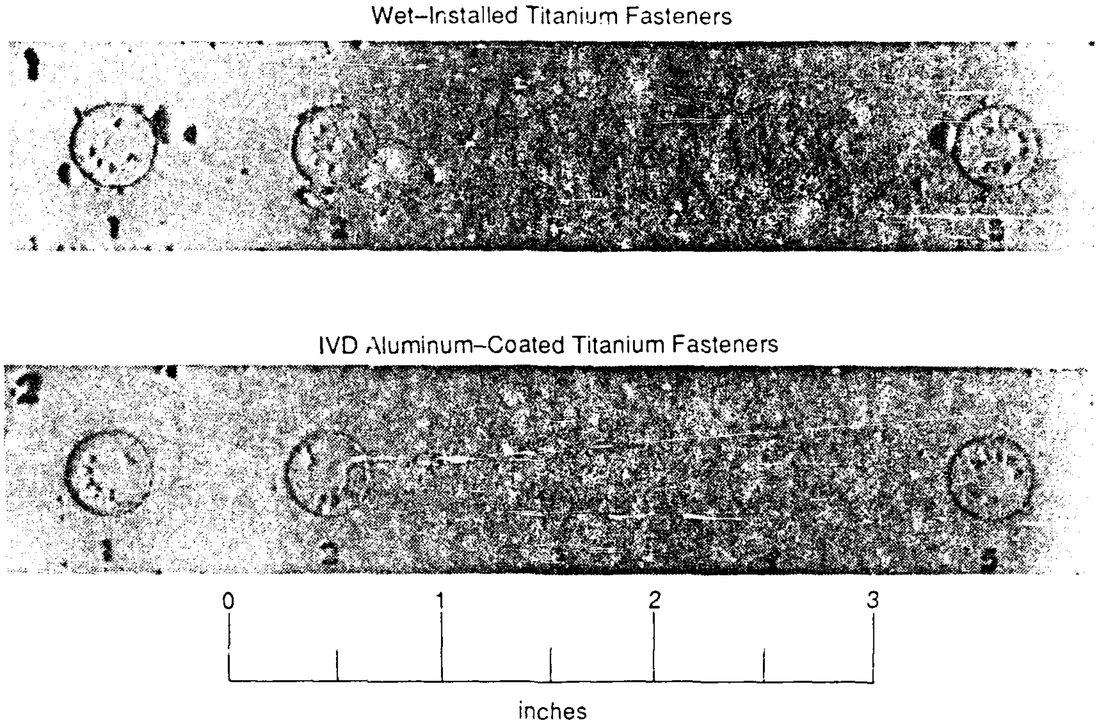


Figure 41. Test Pannels After 28 Days of SO_2 Salt Fog Exposure.

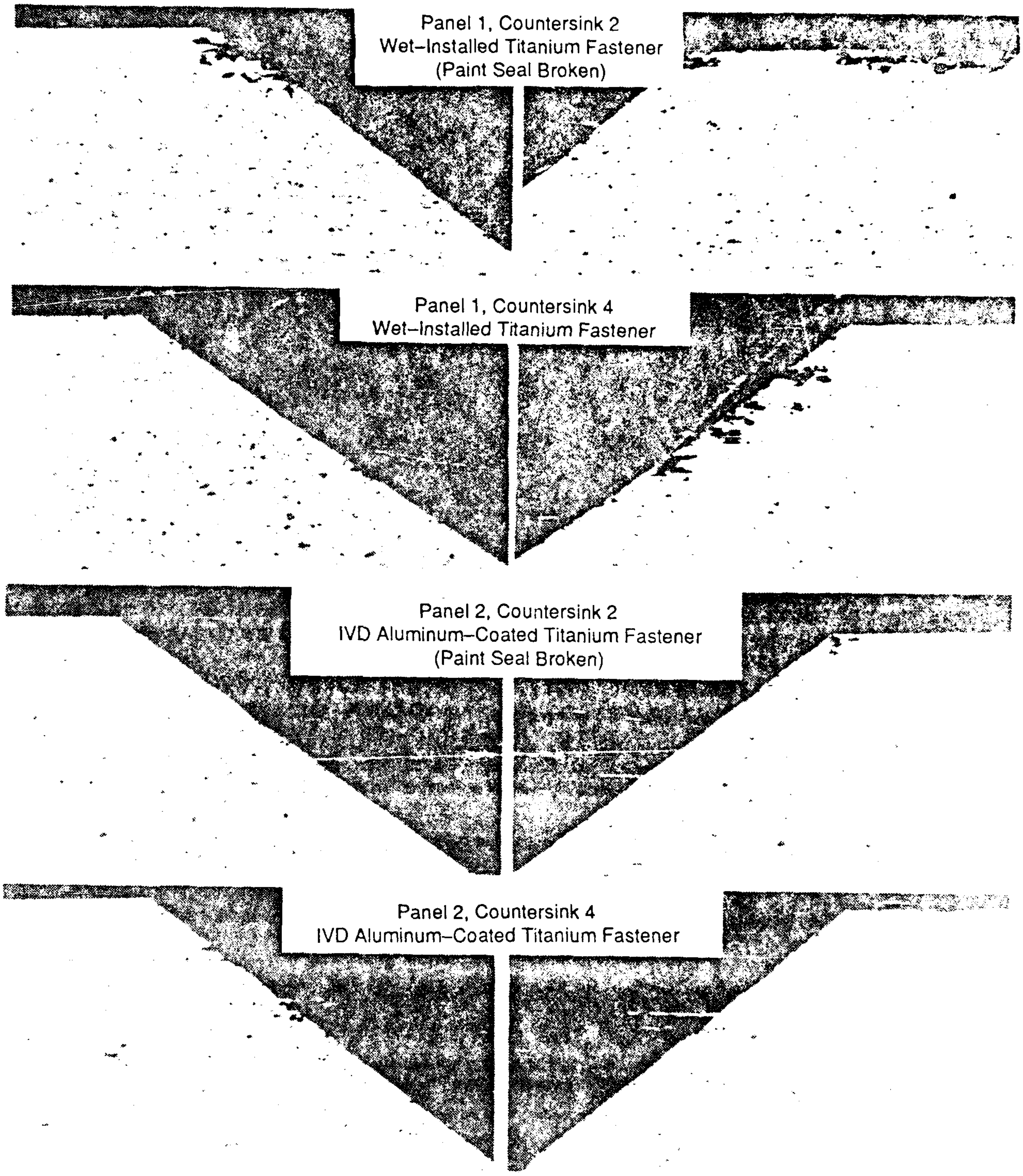


Figure 42. Photomicrographs of Test Panel Countersinks.

As mentioned, cadmium is not normally used on or in contact with titanium because of the possibility of solid metal embrittlement. Figure 43 shows a fractured Ti-6Al-4V titanium alloy surface after exposure to cadmium at 300°F. Boeing compared IVD aluminum and cadmium in an environment conducive to the occurrence of solid metal embrittlement. In this test (Reference 57), four IVD aluminum-coated and four cadmium-plated fasteners were installed in aluminum alloy panels drilled to provide a 0.001 - 0.003-inch interference fit. The fasteners were then stressed up to 80 percent of their ultimate load while the panels were exposed to elevated temperatures. All of the cadmium-plated fasteners failed. None of the IVD aluminum-coated fasteners failed at exposure temperatures up to 650°F.

Mixture of Separated–Grain Facets and Transgranular Cleavage Facets on the Surface of a Fracture in Titanium Alloy TI–6A1–4V That Was Exposed to Solid Cadmium at 149° C (300° F).

Figure 43. Cadmium-Induced Embrittlement Failure.

C. NONMETALLIC SUBSTRATES

Nonmetallic materials such as ceramics, thermoplastics, and composites can be IVD aluminum coated. These materials are used extensively in modern aircraft, spacecraft, and missiles. Applications range from primary structure to electronic enclosures and components. Because these materials are generally dielectric, they may need a conductive coating on exterior surfaces or at selected points for applications requiring electrical grounding or EMIC. IVD aluminum can provide the electrical continuity required for such applications.

Modifications are required to the IVD aluminum process when coating nonmetallic substrates. These modifications are necessary because nonmetallics are generally more temperature sensitive, they produce more outgassing products in the vacuum chambers, and/or their nonconductive nature affects the glow discharge cleaning operation. Processing modifications to apply IVD aluminum to nonmetallic substrates have been successfully demonstrated.

Temperature sensitive nonmetallic substrates can be alternately coated and cooled with gaseous nitrogen while in the vacuum chamber. All IVD aluminum coaters have this cooling capability. An IVD aluminum coating of any desired thickness can be obtained by simply repeating this alternating coating and cooling procedure. The coating performs equally well whether produced in a single coating cycle or from multiple coating and cooling cycles.

Outgassing from nonmetallic substrates is controlled in several ways. The coater's pumping system is sufficient to handle most gas loads. However, if a substrate produces a large outgassing load, it can be baked prior to coating. Also, by limiting the substrate's temperature during coating, the gas load to the pumping system is reduced. Steps should always be taken to prevent excessive outgassing which can adversely affect coating-to-substrate adhesion.

With nonmetallic parts, normal glow discharge cleaning does not take place. To circumvent this problem, the glow discharge can be eliminated and the aluminum coating applied by physical vapor deposition (PVD). PVD processing produces an acceptable coating, but adhesion of the coating is normally not as good as it would be with IVD. An alternate approach is to place a metallic screen behind the nonmetallic part. The metallic screen is then maintained at high voltage, so that the part is within a glow discharge (Reference 73).

Nonmetallic parts are normally solvent-cleaned and lightly grit-blasted before coating. If desired, the part can be lightly glass-bead-peened for an adhesion verification after coating. The adhesion of IVD aluminum on nonmetallic parts is generally acceptable, but not as tenacious as it is on metal parts.

An example of a nonmetallic production part being coated with IVD aluminum is a Raytheon-produced radar wave guide formed by two pieces of ceramic material adhesively bonded together. Thousands of these fragile, ceramic elements have been processed to produce a conductive surface without thermal degradation of the adhesive bond. In a different application, selected areas of quartz lenses were successfully coated with IVD aluminum to produce a reflective surface.

MCAIR has demonstrated that IVD aluminum can be applied to plastic enclosures (Reference 21). A 6-mil coating was deposited without damaging the temperature sensitive plastic material (Figure 44). An IVD copper coating was also deposited onto a plastic enclosure. It provided an electrically conductive basecoat for subsequent electroplating.

IVD aluminum coatings have also been deposited onto carbon-epoxy composites. It is more difficult to obtain a uniform, pinhole-free coating on this substrate than on ceramics or plastics. The carbon fiber is fragile and can be broken if the voltage on the part is too high during glow discharge cleaning or during coating. Nevertheless, acceptable coating adhesion has been obtained on a repeatable basis.

Figure 44. IVD Aluminum-Coated Plastic Enclosure.

In summary, many nonmetallic materials have been successfully coated with IVD aluminum. Processing procedures require modification, but good coating adhesion can be obtained with no substrate degradation.

D. NEODYMIUM-IRON-BORON SUBSTRATES

The use of new materials that greatly increase magnetic properties is changing the permanent magnet industry. Lighter, smaller, and simpler motors are possible using rare-earth alloys like neodymium-iron-boron (NdFeB) as permanent magnet material. Magnets made from this material display the highest magnetic strength ever attained in permanent magnets while offering significant savings in raw materials cost (in relation to other rare-earth alloys). A 1987 study (Reference 74) reported that NdFeB has the potential to capture 50-95 percent of markets shared by conventional alnico, ferrite, and rare-earth samarium-cobalt magnets.

Corrosion is a major problem, however, with NdFeB magnets. The material constituents themselves form a galvanic cell which readily corrodes. Neodymium is one of the least noble metals and, therefore, is sacrificial to almost every other metal. Also, neodymium readily forms a loose oxide in the presence of moisture. Finishes applied over an oxidized NdFeB surface readily flake off. This prevents the use of most standard finishes including "wet" processing like cadmium electroplate and the more permeable coatings such as paints. Adequate protection of these magnets is a major challenge, particularly in the more corrosive environments.

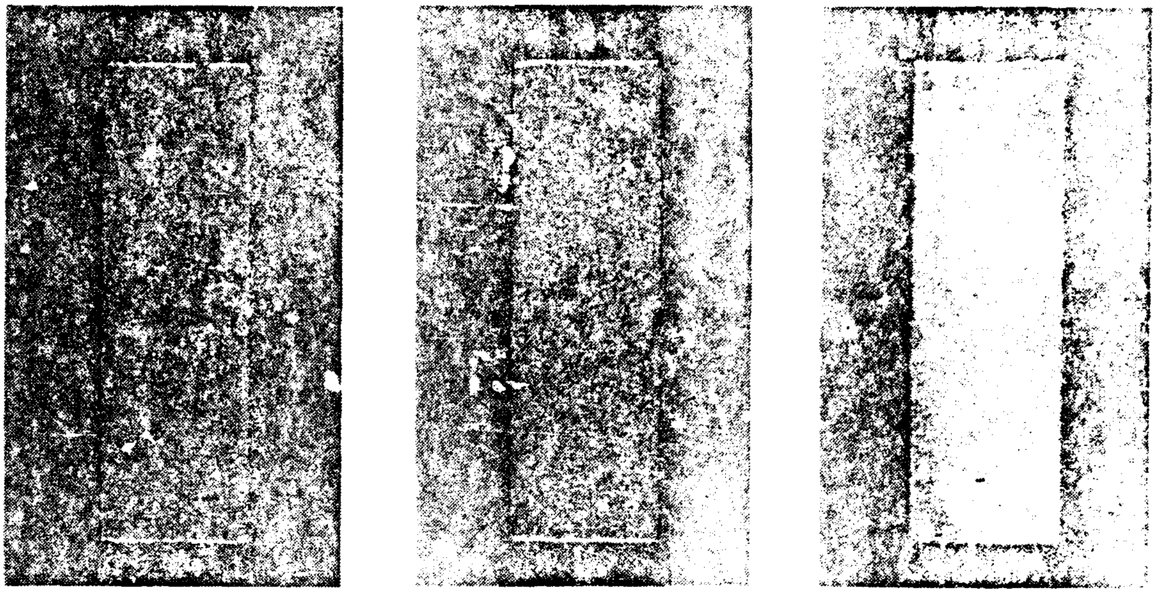
Although neodymium is also sacrificial to both aluminum and cadmium, IVD aluminum has been found to be an effective corrosion-prevention, barrier coating for NdFeB magnets. The IVD processing allows the magnets to stay dry during precleaning (aluminum oxide grit blast) and during coating in the vacuum chamber. IVD aluminum alone has been shown to provide adequate corrosion resistance for applications such as Dataproduct's 3-month, 124°F, 95 percent relative humidity test.

In addition, IVD aluminum provides an excellent base for subsequent topcoating because of its columnar structure, adhesion, excellent coverage, and uniformity. As shown in Figure 45, the corrosion resistance performance of IVD aluminum on NdFeB magnets in a 5 percent neutral salt fog environment can be enhanced with topcoats. MCAIR subsequently developed an IVD aluminum basecoat and Xylar® 101 ceramic sealcoat system which provided 1000-hour protection in a 5 percent neutral salt fog environment (Reference 75).

The use of IVD aluminum on NdFeB magnets has become a standard for several of the largest magnet manufacturers. In addition to providing needed corrosion resistance, coating costs are relatively low as most magnet sizes can be batch-processed in barrels rather than hand-fixtured.

E. DEPLETED URANIUM SUBSTRATES

Depleted uranium (DU) is an abundant byproduct of the nuclear energy industry. Military applications for this dense, malleable material include ballast weights and armor-penetrating munitions. DU is classified as a



IVD Aluminum Coating (Slight Corrosion on Edges)

IVD Aluminum Overcoated with Epoxy Primer (No Corrosion)

IVD Aluminum Overcoated with Epoxy Primer and Polyurethane Topcoat (No Corrosion)

Figure 45. IVD Aluminum-Coated Neodymium-Iron-Boron Magnets after 100 Hours of Neutral Salt Fog Exposure.

"controlled material" because of its radioactivity and, therefore, requires special handling. It is also susceptible to corrosion and forms a loose oxide when exposed to the general environment (Figure 46). This oxide is both toxic and radioactive.

In addition to handling problems, there is also concern for the ability of DU components to function as designed after extended periods in storage and resulting corrosion. A U.S. Army workshop on DU corrosion (Reference 76) reported that hydrogen and chloride ion mechanisms related to corrosion adversely affect surface appearance, cause a loss of material, a decrease in ductility, and a loss of strength. These factors indicate the need for a high performance coating to provide long term protection.

Reference 76 concluded that IVD aluminum was the best of the finishes evaluated for DU. Various electroplated and electroless deposited coatings were included in the evaluation. Both humidity and salt spray tests

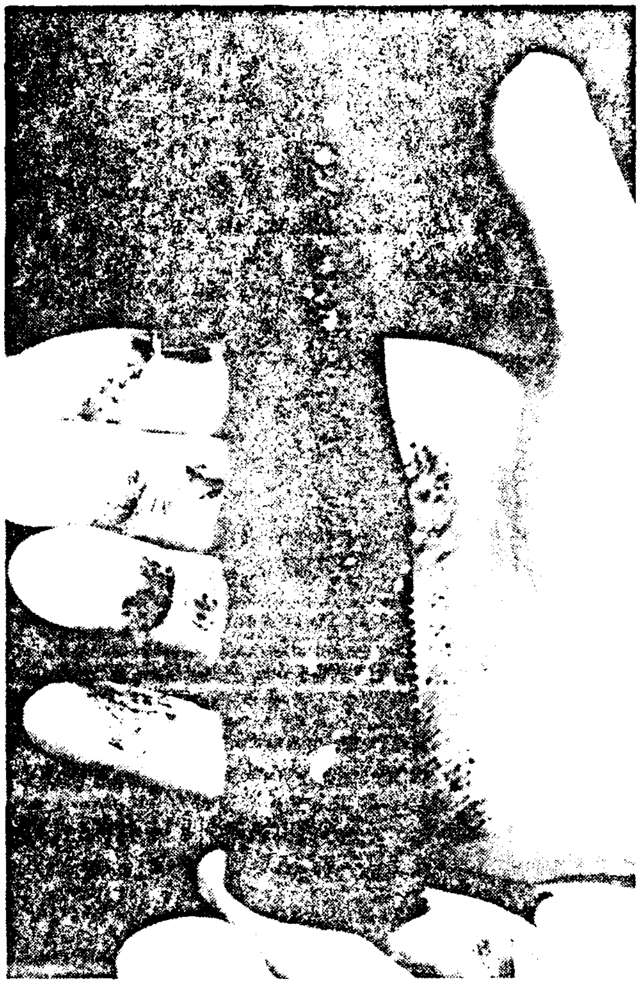


Figure 46. Loose Oxide Formed on Depleted Uranium.

were conducted. The U. S. Army subsequently performed another evaluation of protective finishes for DU (Reference 77). Again, their conclusion was that IVD aluminum provided protection far superior to that of any of the other finishes.

In 1985, the U. S. Army contracted with MCAIR to demonstrate that IVD aluminum was a feasible production process to protect DU penetrator cores for several projectile programs (Reference 78). The program was successfully concluded; a DU penetrator core coated with IVD aluminum is shown in Figure 47. The IVD aluminum process was shown to provide acceptable performance in the following critical areas:

- Corrosion resistance
- Coating adhesion and uniformity throughout a production lot
- Cost effective production fixturing
- Rework capability

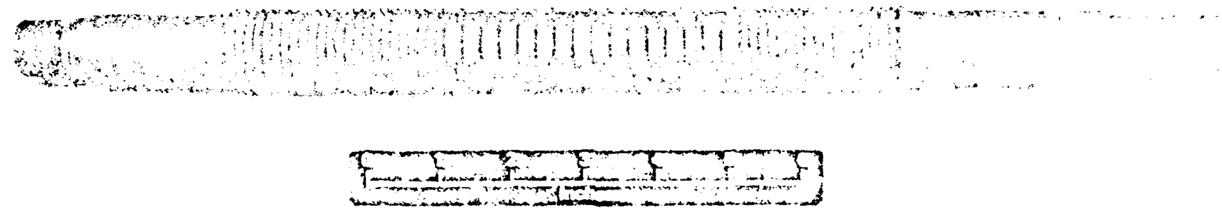


Figure 47. IVD Aluminum-Coated Depleted Uranium Penetrator Core.

Revision B of MIL-STD-1568(USAF), "Materials and Processes for Corrosion Prevention and Control in Aerospace Weapons Systems," is in approval routing and lists IVD aluminum and nickel as the only two acceptable finishes for DU.

F. SUBSTRATES IN CONTACT WITH FUEL AND OTHER FLUIDS

MIL-STD-1568 prohibits the use of cadmium on fuel system components that may contact fuel during operation of the aircraft. The use of cadmium is also prohibited where it may contact fuel or hydraulic fluid by the Navy document MIL-S-5002, "Surface Treatments and Inorganic Coatings for Metal Surfaces of Weapons Systems." IVD aluminum has no such prohibition and has been successfully used in these applications.

A test was conducted by Amphenol (Reference 79) in which mated pairs of IVD aluminum coated plug and receptacle assemblies were immersed in various lubricants, hydraulic fluids, and fuels. These fluid immersion tests were conducted with controlled immersion times and fluid temperatures as required by the appropriate military specifications (Reference 80). Amphenol stated that all specimens were satisfactory and that there was no evidence of any surface corrosion or any electrolytic action between the mating shells.

Boeing tested the resistance of IVD aluminum to hydraulic fluid and paint stripper (Reference 81). The hydraulic fluid resistance test consisted of immersing fasteners in BMS 3-11 fluid for 30 days at 70± 5°F. The coating adhesion and visual appearance were not affected by the test. Fasteners were also immersed in Turco 5351 paint stripper at 70±5°F for 24 hours, and again no adverse effects were found.

Pratt & Whitney tested various corrosion resistant finishes including IVD aluminum and diffused nickel-cadmium on 410 alloy steel stators (Reference 17). As part of their tests, the finished stators were immersed in full-strength B&B 3100 engine cleaner for 4 hours. Although none of the finishes appeared to be harmed, the engine cleaner was analyzed by atomic absorption spectrophotometry. No aluminum was found in the cleaning solution indicating all aluminum based coatings resisted attack by the cleaner. However, they did find cadmium from the diffused nickel-cadmium-plated stator.

SECTION VII

REWORK AND FIELD REPAIR

The incidence of in-house rework and field repair of IVD aluminum coated parts is minimal. As previously discussed in Section II(A), coating-to-substrate adhesion for IVD processing is excellent. In addition, most processors glass-bead-peen the coating which provides a 100 percent nondestructive adhesion test. Poor to marginal coatings are detected with this procedure which is a more thorough quality check than standard tape and bend-to-break testing. Also, the coating is soft and ductile; it therefore resists chipping and will not rip-off with mechanical abuse. However, as is the case for any finish, incorrect processing procedures can necessitate the need for in-house rework. Also because the IVD aluminum coating is soft, like cadmium, coated parts in service are subject to scratches and can be abrasively damaged. Rework and repair techniques are therefore necessary.

A. IN-HOUSE REWORK AND REPAIR

Procedures have been established covering poor coating adhesion, incorrect thickness, repair of scratches, bare areas in the coating, and scheduled ALC maintenance. These procedures are summarized below.

1. Poor Coating Adhesion

a. For general or extensive non-adhesion:

(1) Strip existing IVD aluminum coating by chemical (sodium hydroxide) or mechanical (glass bead or aluminum oxide grit) procedures.

NOTE: Embrittlement relief baking (375°F for 24 hours) is required on high strength steel parts after chemical stripping. Mechanical stripping of a normally adherent IVD aluminum coating is difficult.

(2) Recoat with IVD aluminum.

b. For local coating non-adhesion:

(1) Peen coating surface with glass beads at 60 psi.

(2) Lightly grit blast coating surface at 30 psi with aluminum oxide grit.

(3) Recoat over bare area and existing coating (mask only as required to maintain tolerances).

2. Incorrect Coating Thickness

a. When the coating is too thin:

(1) Overcoat to correct thickness with IVD aluminum.

b. When the coating is too thick:

(1) Strip existing IVD aluminum coating by chemical (sodium hydroxide) or mechanical (aluminum oxide grit) procedures.

(2) Recoat with IVD aluminum.

3. Scratches In the Coating

a. When scratches occur before assembly:

(1) Blend in scratch(es) by glass bead peening at 40 psi.

(2) Chromate or rechromate the burnished area. Brush chromating is acceptable.

b. When scratches occur after assembly:

(1) Follow an applicable field repair procedure.

4. Bare Area in the Coating

a. Follow procedure 1. for local coating non-adhesion.

5. Scheduled ALC Maintenance

a. Strip existing IVD aluminum coating by chemical (sodium hydroxide) or mechanical (aluminum oxide grit) procedures.

b. Recoat with IVD aluminum.

B. FIELD REPAIR

Procedures have been established covering scratches in the coating and bare areas in the coating. For bare areas, the repair can be made using several methods, including primer and paint, brush cadmium, and sacrificial aluminum-based paint systems. These procedures are presented below.

1. Scratches In the Coating

a. Blend in scratch(es) by burnishing the damaged area and an area 1/4-inch wide around the periphery of the damaged area with an abrasive pad.

b. Brush-chromate the burnished area.

2. Bare Areas In the Coating

a. The following general procedures are applicable to all field repairs of bare areas:

(1) Remove paint from a 1/4-inch wide section and scuff around the periphery of the damaged area.

(2) Solvent clean the repair area to remove oil and greases.

(3) Abrasively remove any corrosion products.

(4) Repair area using appropriate method presented below.

(5) Check the adhesion of the repair by tape testing.

b. For prime and paint repair:

(1) Brush-chromate the repair area.

(2) Apply 1 coat of epoxy primer.

(3) Apply 1 coat of polysulfide.

(4) Apply 2 coats of polyurethane topcoat.

c. For brush cadmium repair:

(1) Brush cadmium plate to a minimum thickness of 0.75 mil where tolerances allow.

(2) Embrittlement relieve (375°F for 24 hours) as applicable.

(3) Brush-chromate the repaired area.

(4) Apply paint primer and topcoat as applicable.

d. For Alseal® 518 (sacrificial aluminum based paint) repair:

(1) Apply Alseal® 518 per the manufacturer's specification.

(2) After curing (requires elevated temperature), burnish rather than bake the coating to make it electrically conductive. Hand burnish if there is no access to a glass bead peener.

(3) Brush-chromate the repaired area.

(4) Apply paint primer and topcoat as applicable.

e. For Sermetel® 249/Sermetel® 273 (sacrificial aluminum-based paint) repair:

(1) Blend any sharp edges between the undamaged coating and the substrate.

(2) Apply 0.8-1.0 mil of Sermetel® 249 per the manufacturer's specification. Cure at room temperature for at least 1/2 hour.

(3) Apply Sermetel® 273 catalyst over the dried Sermetel® 249. Allow the catalyst to set for 1 hour and rinse with deionized water.

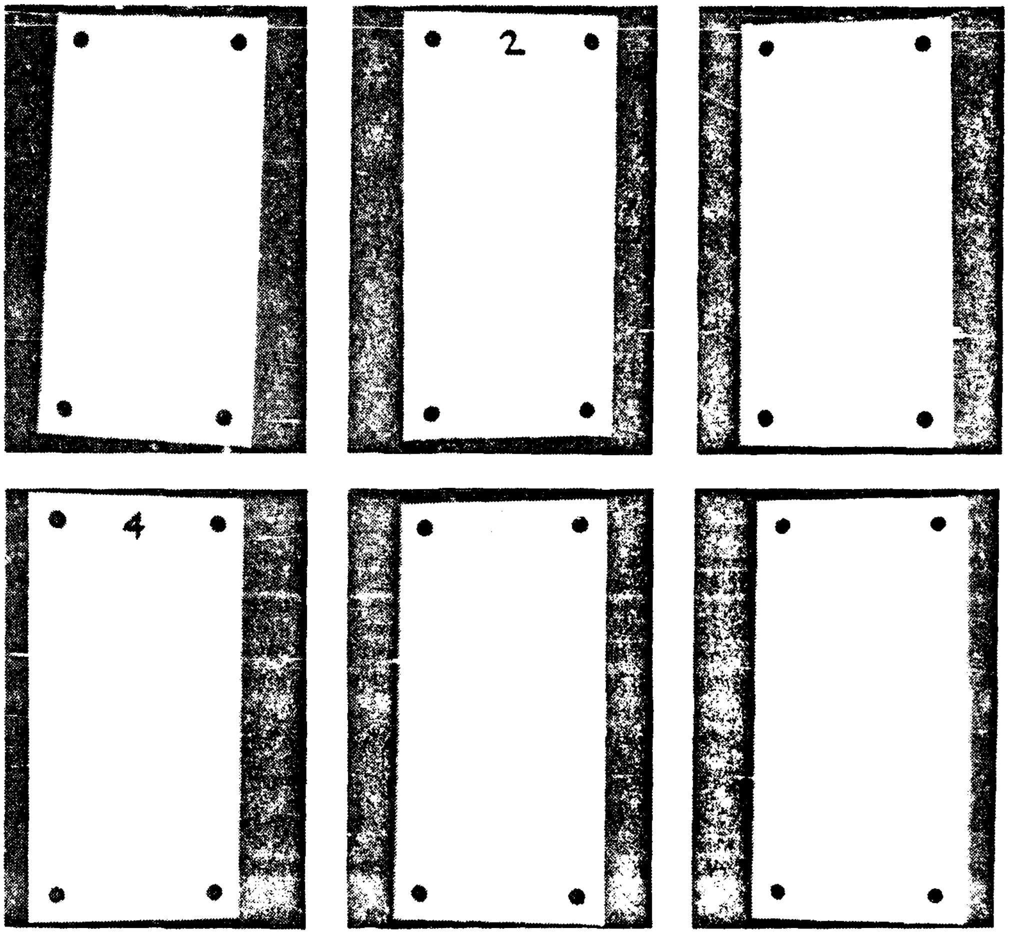
(4) Smooth out any roughness between the IVD coating and Sermetel®.

(5) Brush-chromate the repaired area.

(6) Apply paint primer and topcoat as applicable.

MCAIR tested the corrosion resistance of the "prime and paint repair" on six 3- by 6-inch 4130 alloy steel panels (Reference 82). The panels had their paint and IVD aluminum coatings removed from a 0.5- by 1.0-inch area in the center of the panel and the "prime and paint repair" applied. A diagional line was scratched in the coating systems on three panels. The panels were then subjected to the Naval Air Development Center SO_2 salt fog exposure test for 28 days. As shown in Figure 48, there were no signs of corrosion.

MCAIR evaluated brush cadmium plating as a field repair for IVD aluminum on twelve 1- by 4-inch 4130 alloy steel panels (Reference 83). The IVD aluminum was removed from the center section of each panel and replaced with brush-applied cadmium in thicknesses of 0.5 and 0.75 mil. Six of the brush cadmium repair specimens were chromated (Type II); the others were not (Type I).



Epoxy Primer-Polysulfide Sealant - Polyurethane Topcoat

Figure 48. Prime and Paint Repair of IVD Aluminum-Coated Panels After 28 Days of SO_2 Salt Fog Exposure.

Half of the specimens representing each brush cadmium plating category were exposed to a neutral salt fog exposure for either 19 or 28 days and the remaining specimens were exposed to an SO_2 salt fog environment for 6 days. The chromated, 0.75-mil thick cadmium finish offered the best corrosion resistance in neutral salt (see Figure 49).

Two 0.5 mil, nonchromated cadmium repair specimens failed (red rust) in 19 days in neutral salt and all of the cadmium repair specimens failed the 6-day, SO_2 salt fog exposure. However, cadmium is known to perform poorly in acidic environments as discussed in Section III(B). Also, it should be noted that the test panels were not painted after application of the brush cadmium, and painting would be a normal part of field repair.

MCAIR did not conduct a formal test of Alseal® 518 as a repair procedure. However, they did demonstrate that Alseal® 518 can be successfully applied to damaged IVD aluminum-coated steel panels. Also, Alseal® 518 was applied to an alloy steel panel, scribed and exposed to a 5 percent neutral salt fog environment for 9,000 hours without red rust (Reference 64).

Cleveland Pneumatic Company (CPC) evaluated the corrosion resistance of various IVD repair procedures recommended by MCAIR as well as several other potential techniques, notably Sermetel® 249, on 4- by 6-inch 4130 alloy steel panels (Reference 65). The repair material was applied to an area 1-inch in diameter. The panels were then exposed to a 5 percent neutral salt fog environment for 4 weeks. CPC reported that:

o Alseal® 518 is not a feasible repair for them because it does not cure at room temperature.

o Three repair methods which were tested, namely, Sermetel® 249, brush-cadmium plating using the Dalic® 2023 solution, and the application of primer, sealant, and paint, provided acceptable corrosion-resistance protection.

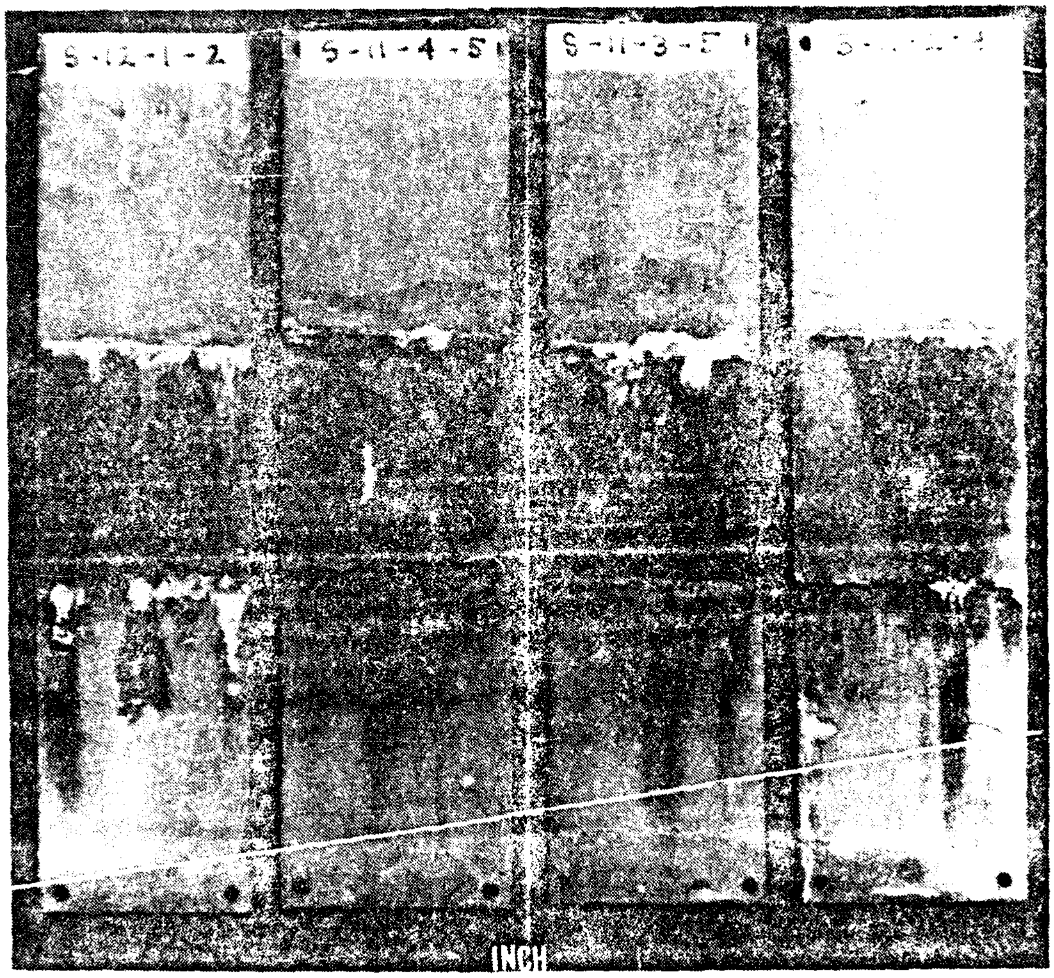
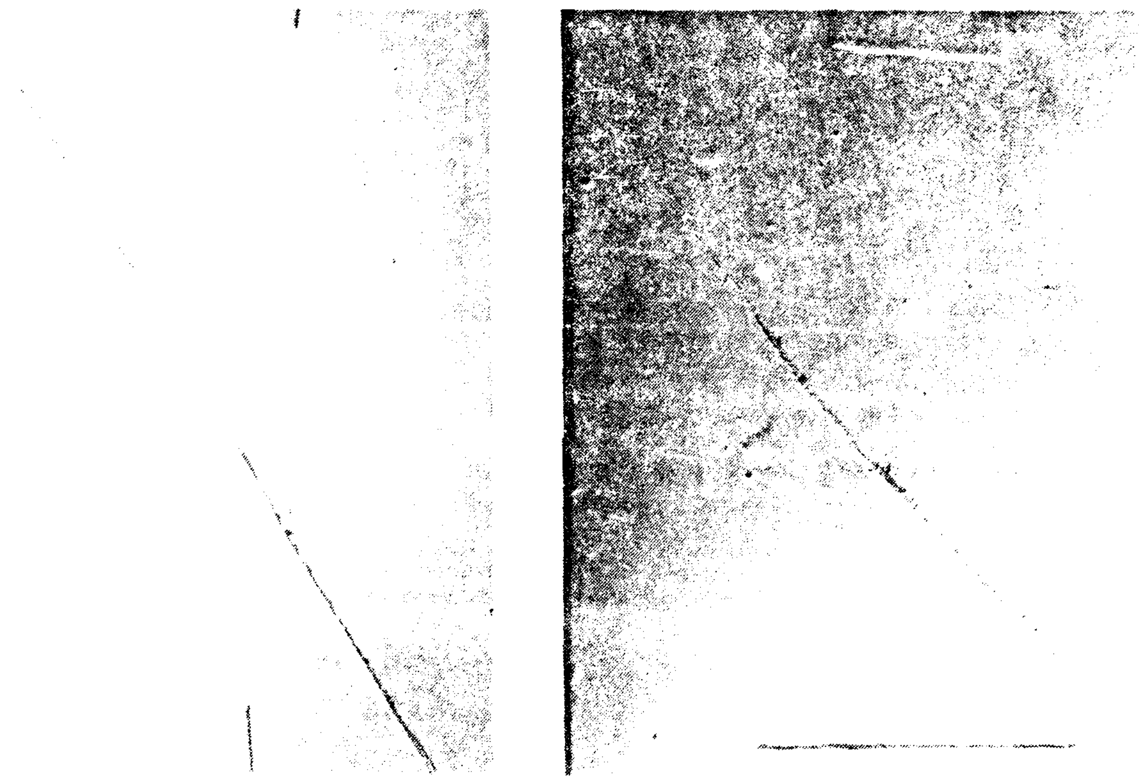


Figure 49. Brush Cadmium Repair of IVD Aluminum-Coated Panels After 28 Days of Neutral Salt Fog Exposure.

o Of the three acceptable repair methods, the Sermetel® 249 used with the Sermetel® 273 catalyst offered the greatest advantages to them. It was relatively easy to apply, required few tools or materials, cured at room temperature, and offered excellent salt spray corrosion resistance (Figure 50).



280–Hour Neutral Salt Fog Exposure   672–Hour Neutral Salt Fog Exposure

Figure 50. Corrosion Resistance of Sermetel®249/Sermetel®273 Repair.

o The interfaces between the Sermetel® and IVD aluminum coatings must be blended to prevent the formation of bubbles in subsequent paint coatings. MCAIR rejected the Sermetel® 249/273 repair without further testing because of the formation of bubbles and staining in the repair area.

In addition to the repair procedures discussed above, arc-spray aluminum may also be a feasible field repair. MCAIR originally tested 4- by 6-inch IVD aluminum-coated alloy steel panels that had arc-spray aluminum applied to bare areas in the form of diagonal strips ranging in width from 1/16 to 1/4 inch (Reference 86). MCAIR reported at the time of these early tests that the corrosion resistance of the repaired panels was acceptable in 5 percent neutral salt (2,164 to 7,248 hours before red rust), but local nonadhesion of the arc-sprayed coating was present on all the panels at the interface with the IVD aluminum coating. MCAIR later retested arc-sprayed aluminum (Reference 84). In this later test, the IVD aluminum coated alloy steel panels were partially stripped by grit blasting to simulate damage. The areas around the damaged sections were masked, and the damaged areas were coated with arc-sprayed aluminum. After glass bead peening at 40 psi, the arc-sprayed coating was smooth, adherent and uniform in thickness (7 mils). After chromating, the panels were exposed to 2,184 hours of 5 percent neutral salt spray without substrate corrosion. MCAIR reported that additional testing, including the development of application procedures, should be conducted before this method could be recommended for field repair. Table 28 summarizes the various field repairs for bare areas in IVD aluminum coatings.

TABLE 28. FIELD REPAIR TECHNIQUES.

Repair Method	Comment
Prime and Paint	Acceptable. But No Sacrificial Finish on Substrate
Brush Cadmium	Embrittlement Relief Required for High Strength Steel
Alseal 518	Requires Minimum of 400°F Curing Temperature
Sermetel 249/273	Cures at Room Temperature With 273 Catalyst
Arc-Spray Aluminum	Displays Potential. But More Work Required

SECTION VIII

PROCESSING COST

In an effort to compare IVD aluminum and cadmium, the recurring labor and material costs involved in processing a given type generic part were examined. This examination included a study of hazardous waste treatment, collection, and disposal costs. An estimate of the capital costs involved was added to obtain a comparative picture of one process versus another.

Processing costs can be affected by many different variables. In the first place, there are many different cadmium processes. Large variation in part sizes and shapes, different quantities of parts being processed at any one time, different equipment or accessories being used, different proficiencies of operators, different states of facility modernization, etc., are examples of variables which significantly affect processing costs. Even if all of these variables were held constant, costs will still vary among processors. There are different local regulations affecting processing procedures as well as different accounting methods for allocating costs. For this reason, the effort reported herein is necessarily limited to providing only a general idea of the relative costs of the commonly used cadmium processes and the IVD aluminum process.

In comparing the IVD aluminum process with the "bright" cadmium, low-embrittlement cadmium, vacuum cadmium, and diffused nickel-cadmium processes, the following general conclusions can be drawn:

o The direct processing costs required for IVD aluminum is generally higher than that required for vacuum and "bright" cadmium and less than that required for low-embrittlement cadmium and diffused nickel-cadmium.

o IVD aluminum processing has no recurring pollution-related costs. The pollution control costs for all cadmium processing (including capital, treatment, collection, and disposal of hazardous wastes) are major cost factors.

o The capital equipment outlay for IVD aluminum processing is in the same general category as that required for cadmium processing if the pollution control equipment required for cadmium is included.

o When the direct processing costs, recurring pollution control costs, and capital costs are combined, IVD aluminum appears to cost more than vacuum cadmium, approximately the same as "bright" cadmium, and less than low-embrittement cadmium and diffused nickel-cadmium.

In surveying different metal finishing operations to obtain cost information on IVD aluminum versus cadmium processing, the most meaningful data was obtained from independent contractors or "job-shops" (Reference 67). Two facilities were visited and both were proficient in IVD aluminum and cadmium processing. A variety of parts were being processed; operators were well-trained, and equipment/accessories were relatively state-of-the-art. Also, meaningful information on the contribution to total cost of the various cost factors was obtained. These costs were then averaged with MCAIR in-house costs. Table 29 is a summary of the relative costs for cadmium and IVD aluminum processing of a generic part with an envelope of approximately 36 x 12 x 8 inches including recesses and protrusions.

TABLE 29. RELATIVE COSTS OF IVD ALUMINUM VERSUS CADMIUM PROCESSING.

Cost Factor	Cost for Generic 36 × 12 × 8 in. Detail				
	IVD Aluminum	Vacuum Cadmium	"Bright" Cadmium	Low-Embrittlement Cadmium	Diffused Nickel-Cadmium
Direct Processing	$105	$70	$ 80	$126	$121
— Labor	65%	76%	68%	84%	60%
— Capital	35%	24%	32%	16%	40%
Pollution Control	—	$ 4	$ 25	$ 16	$ 14
— Recurring		67%	67%	67%	67%
— Capital		33%	33%	33%	33%
Total	$105	$74	$105	$142	$135
Future Direction	▼	–	▲	▲	▲

The direct processing costs shown in Table 29 are a combination of recurring and capital costs. The major recurring cost is labor which constitutes about 65 percent of the total cost. Other recurring costs such as utilities, chemicals, aluminum, cadmium, etc. are about equal for the various processes and are not shown in the comparison. Table 30 is a flow chart showing the processing steps required by MCAIR specifications for the various processes. An approximate labor requirement for each step is shown in

TABLE 30. PROCESSING FLOW CHARTS AND LABOR REQUIREMENTS FOR IVD ALUMINUM AND CADMIUM PROCESSES.

IVD Aluminum (136 Person-Minutes Detail)	Vacuum Cadmium (106 Person-Minutes Detail)	Electroplated "Bright" Cadmium (107 Person-Minutes Detail)	Low-Embrittlement Cadmium (211 Person-Minutes Detail)	Diffused Nickel-Cadmium (140 Person-Minutes Detail)
Vapor Degrease (14)*	Vapor Degrease (14)*	Vapor Degrease (14)*	Vapor Degrease (14)*	Vapor Degrease (14)*
Grit Blast (32)	Grit Blast (32)	Grit Blast (16)	Grit Blast (32)	Grit Blast (16)
		Alkaline Clean (10)	Water Wash (2)	Anodic Clean (10)
		3-Step Water Rinse (10) (Hot, Cold, Deionized)		3-Step Water Rinse (10) (Hot, Cold, Deionized)
		Pickle (2) (Hydrochloric Acid)		Pickle (2) (Hydrochloric Acid)
		Cold Water Rinse (3)		Cold Water Rinse (3)
				Nickel Plate (10) (3 Details Per 30 min Cycle)
				2-Step Water Rinse (3) (Cold, Hot)
Aluminum Coat (52) (4 Details Per 210 min Cycle)	Cadmium Coat (40) (2 Details Per 30 min Cycle)	Cadmium Plate (10) (4 Details Per 40 min Cycle)	Cadmium Plate (30) (4 Details Per 120 min Cycle)	Bright Cadmium Plate (10)
Glass Bead Peen (18)		2-Step Water Rinse (3) (Cold, Hot)	4-Step Water Rinse (6) (Cold, Neutralizing, Cold, Hot)	2-Step Water Rinse (3) (Cold, Hot)
		Blow Dry (4)	Blow Dry (4)	Blow Dry (4)
Inspect (6) (Adhesion and Thickness)	Inspect (6) (Adhesion and Thickness)	Inspect (6) (Adhesion and Thickness)	Inspect (6) (Adhesion and Thickness)	Inspect (6) (Adhesion and Thickness)
			Apply Temperature Spot Indicator (1)	
			Embrittlement Relieve (15) (24 Hour Cycle)	
		Alkaline Clean (4)	Inspect (5) (Monthly Embrittlement Relief Test)	Alkaline Clean (4)
		2-Step Water Rinse (6)	Magnetic Particle Inspection (40)	2-Step Water Rinse (6) (Hot, Cold)
		Dip in Cadmium Plating Solution (3)	Vapor Degrease (14)	Dip in Cadmium Plating Solution (3)
		Cold Water Rinse (2)	Wet Abrasive Clean (28)	Cold Water Rinse (2)
Chromate Conversion Coat (4)	Chromate Conversion Coat (4)	Chromate Conversion Coat (4)	Chromate Conversion Coat (4)	Chromate Conversion Coat (4)
Cold Water Rinse (2)	Cold Water Rinse (2)	Cold Water Rinse (2)	Cold Water Rinse (2)	Cold Water Rinse (2)
Blow Dry (4)	Blow Dry (4)	Blow Dry (4)	Blow Dry (4)	Blow Dry (4)
Inspect (4)	Inspect (4)	Inspect (4)	Inspect (4)	Inspect (4)
				Diffuse at 630 F (15)
				Inspect (5)

* [illegible]

person-minutes on the flow chart. Processing steps that, when required, would be common to all of the processes such as masking are not shown. It is assumed that the "bright" cadmium process is used for low-strength steel applications (no hydrogen embrittlement relief), and low-embrittlement cadmium is used for high-strength steel applications (hydrogen embrittlement relief required). Both the IVD aluminum and vacuum cadmium processes can be used for high-strength steels without the hydrogen embrittlement relief step. Low-embrittlement cadmium is the most laborious process because of steps taken such as baking and magnetic particle inspection to assure the part is not affected by hydrogen embrittlement. Diffused nickel-cadmium requires the most processing steps; vacuum cadmium the least. The labor cost per detail was derived by multiplying the total person-minute requirement for each process by 30 dollars per hour. This amount is thought to be representative of ALC and MCAIR labor costs.

The approximate direct processing capital costs for the various processes are shown in Table 31. The IVD aluminum capital cost includes the coater and dedicated equipment such as a grit blaster and glass bead peener. The vacuum cadmium cost includes the coater and a dedicated grit blaster. The bright cadmium capital cost includes wet tanks, rectifiers, an overhead crane, an exhaust system, sump pumps, and plumbing expenses. The low-embrittlement cadmium capital cost is similar to bright cadmium with the addition of a furnace for embrittlement relief. The diffused nickel-cadmium capital cost is similar to that for low-embrittlement cadmium (furnace for nickel-cadmium

TABLE 31. DIRECT PROCESSING CAPITAL COSTS.

Process	IVD Aluminum	Vacuum Cadmium	"Bright" Cadmium	Low-Embrittlement Cadmium	Diffused Nickel-Cadmium
Capital Cost	$600,000	$360,000	$320,000	$350,000	$480,000
Cost Per Hour[a]	$43	$26	$23	$25	$34
Cycle Time (hr) Per Detail	0.87[b]	0.67[b]	1.15[c]	0.80[c]	1.37[c]
Cost Per Detail	$37	$17	$26	$20	$47

a Cost per hour represents the capital cost amortized over 7 years at 2000 hours per year

b Capital cycle time for the vacuum processes is coater cycle time divided by the number of details per cycle (Table 30)

c Capital cycle time for the wet processes is the sequence of processing steps (Table 30) requiring the continual use of the overhead crane

— For "bright" cadmium, it starts with alkaline clean and ends with chromate conversion coating

— For low-embrittlement cadmium, it starts with water wash and ends with inspection of adhesion and thickness

— For diffused nickel-cadmium, it starts with anodic cleans and ends with chromate conversion coating diffusion) with the addition of tanks for nickel plating. These costs reflect new, state-of-the-art equipment. Capital costs for the wet processes have been adjusted to reflect common usage of such items as grit blasters, overhead cranes, strip tanks, and plumbing. Equipment common to all of the processes and/or common to a number of other processes such as vapor degreasers, chromate tanks, and magnetic particle inspection booths are not included. Capital cost per hour was derived by amortizing capital costs over seven years on a one shift basis. Please note that this cost per hour can vary widely according to accounting methods and equipment utilization. A two shift usage over seven years, for instance, would reduce the capital cost per hour by 50 percent.

Figure 51 is a flow chart representing the typical hazardous waste treatment cycle for cadmium. The rinse water and overflow from cadmium plating tanks and cadmium strip tanks flow into a holding tank where the waste water is analyzed. The waste water is then transferred into a treatment tank for cyanide destruction through a series of chemical steps. The metal hydroxides are precipitated to the bottom of the tanks. The clean liquid on top of the tank is then tested and discharged into the sewer. The metal sludge is transferred into a filter press or centrifuge. The filtrate (clean liquid portion coming from the filter press) is further analyzed before release to the sewer. The dewatered metal sludge is then further reduced in volume by drying before being placed in approved containers for disposal as hazardous waste.

The pollution control cost shown in Table 29 is the cost associated with the Figure 51 waste treatment cycle. Table 32 is an approximate breakdown of these costs which are an average of MCAIR and "job-shop" costs. Labor once again is the major recurring cost factor. However, for pollution control, the combination of chemical, utility, waste disposal, and miscellaneous costs are a significant recurring cost factor. Capital cost per hour was derived by amortizing capital costs over seven years on a one-shift basis.

The total cost shown in Table 32 is typical for waste treatment plants in which several metal finishing processes in addition to the cadmium process are treated. As a result, the pollution control costs for the various cadmium

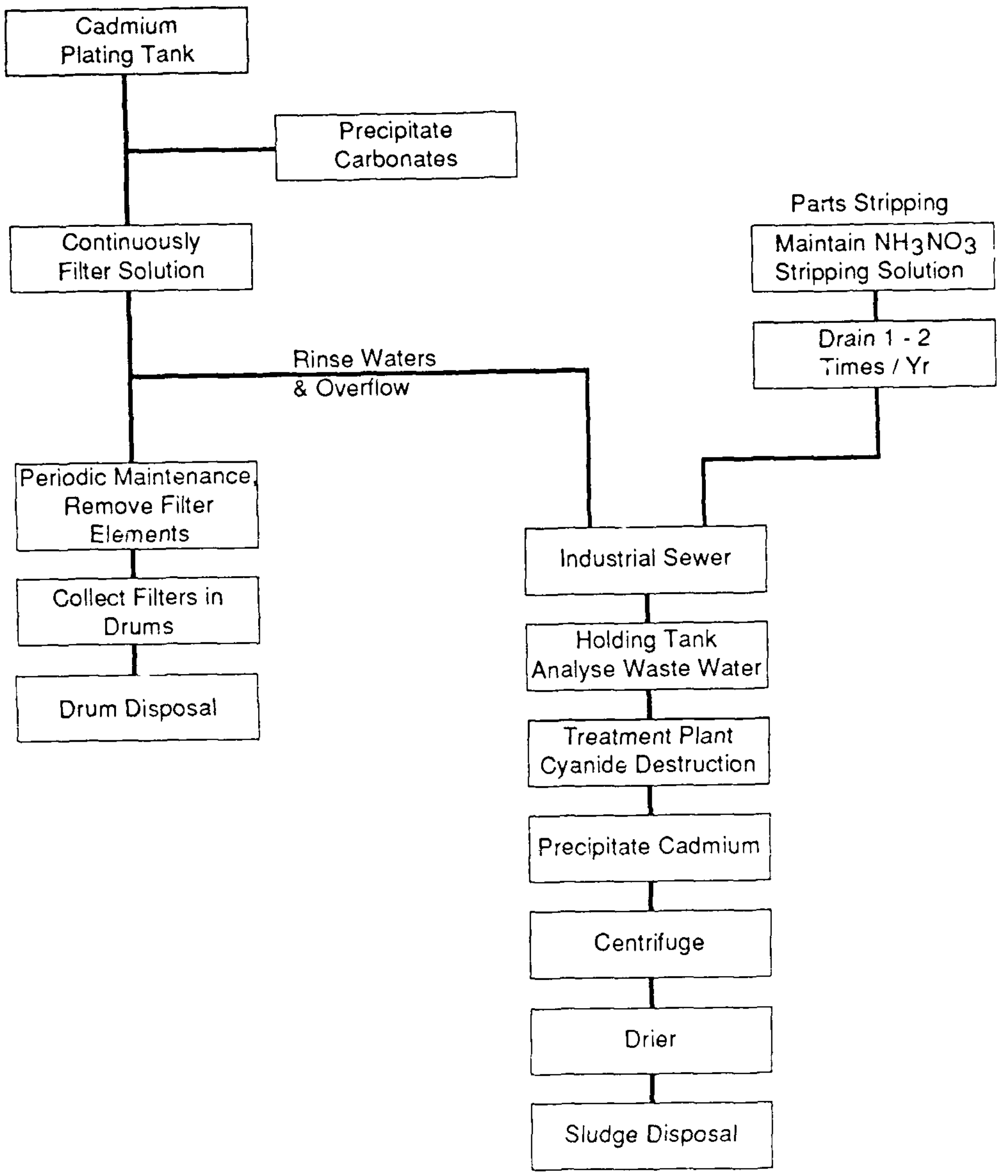


Figure 51. Pollution Control – Flow Chart For Hazardous Waste Treatment and Disposal of Cadmium.

TABLE 32. WASTE TREATMENT PLANT COSTS.

Cost Factor (Hourly Cost)	Cost of Waste Treatment Facility
Recurring	$ 86
Labor	38% – Tank Maintenance, Analysis, Records
Chemicals	16% – Cyanide Destruction, Cadmium Precipitation
Utilities	26% – Water, Electricity
Disposal	17% – Hazardous Waste: Cadmium Sludge, Tank Filters
Miscellaneous	3% – OSHA Compliance, Permits, Insurance
Capital	$ 42 – Amortized on 7 Year, 2,000 Hour Year Basis
Total	$128 – Combination of Recurring and Capital Costs

processes are factored based on estimated usage of the waste treatment facility. The factored cost per hour is shown in in Table 33. The Table 29 pollution control cost is derived from Table 33.

TABLE 33. POLLUTION CONTROL COST PER DETAIL.

Process	IVD Aluminum	Vacuum Cadmium	"Bright" Cadmium	Low-Embrittlement Cadmium	Diffused Nickel-Cadmium
Cost Per Hour[1]	—	$6	$22	$20	$10
Cycle Time (hr) Per Detail	0.87	0.67	1.15	0.80	1.37
Cost Per Detail	—	$4	$25	$16	$14

Note
(1) Assume a treatment facility usage factor of 17% for "bright" cadmium, 16% for low-embrittlement cadmium, 8% for diffused nickel-cadmium and 5% for stripping vacuum cadmium fixtures and shields

Pollution control costs, especially capital cost, would be considerably higher for a plating shop with a limited number of processes requiring pollution control. It should also be noted that the capital cost average is conservative. MCAIR, for instance, invested $625,000 to treat rinsewater from several metal finishing operations in 1970 (Reference 90). Since then, the system has been up-graded with a drainage control system ($13,480), backup generator ($4,625), centrifuge ($200,000), and new storage tank ($35,000). None of these costs were increased to current dollars. There are no pollution control costs associated with IVD aluminum.

The costs analysis presented in this section is for a given point in time. Regardless of the effort to present data as current as possible, it became evident that the finishing industry is experiencing a rapidly changing business environment which will greatly affect future costs. The consensus opinion, however, on the direction of these costs is unequivocal---the costs of all cadmium processing is increasing rapidly relative to IVD aluminum processing due to environmental pollution-related laws and regulations.

Besides being pollution-free, IVD aluminum processing has an additional cost-related advantage over cadmium processing. Cadmium is a mature process within the finishing industry, whereas IVD aluminum processing is in a growth phase and is experiencing major productivity improvements as its acceptance and usage increases. Within the past few years, for example, a rotary rack accessory was developed to rotate parts inside the IVD vacuum chamber during the coating cycle. This eliminates the need to turn some parts over by hand after coating one side, and then go through a second pumpdown and coating cycle. With this accessory, processing time is reduced by approximately 50 percent. The rotary rack accessory is shown in Figure 52.

A dual-barrel accessory, shown in Figure 53, for coating large numbers of small parts by barrel tumbling was also recently developed. This accessory increases the amount of parts processed in a single coating cycle by approximately 100 percent. A third example of recent productivity improvements is the use of a cryopumping system to shorten pumpdown times. Without the cryopump, pumpdown times under humid atmospheric conditions may be

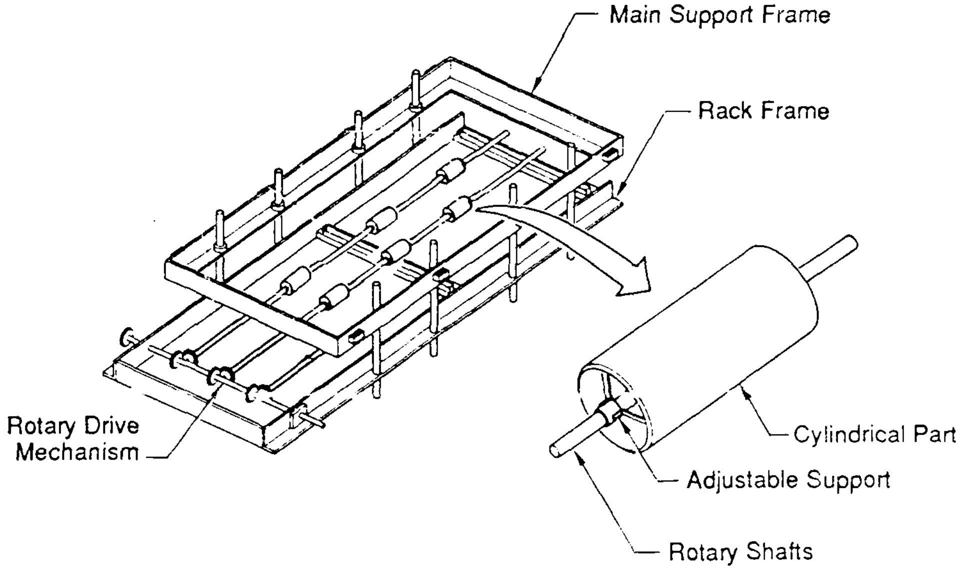


Figure 52. Rotary Fixture for IVD Aluminum Processing.

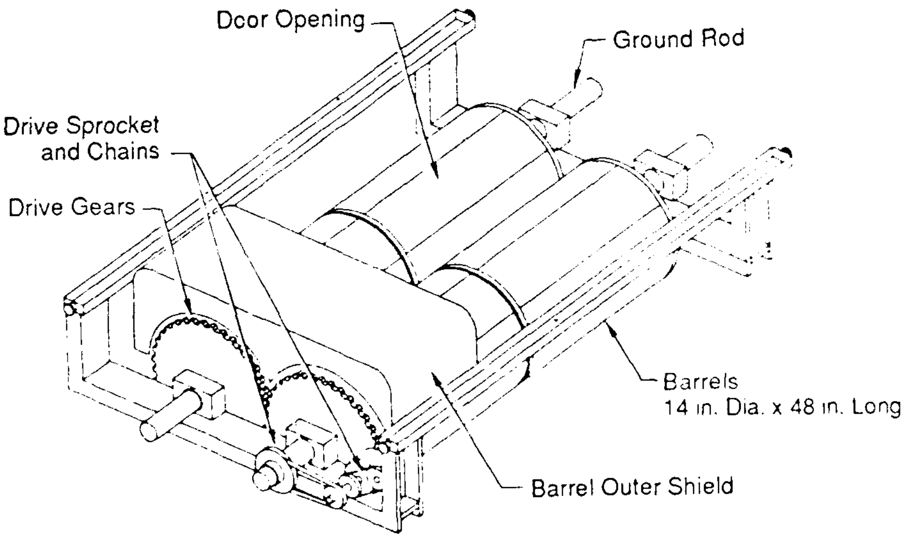


Figure 53. Dual Barrel Accessory for IVD Aluminum Processing.

as long as 1 1/2 hours and represent 75 percent of a two hour processing cycle. With the cyropump, the total cycle time can be shortened to about 1 hour, a reduction of 50 percent. Figure 54 shows pumpdown times with and without a cryopumping system.

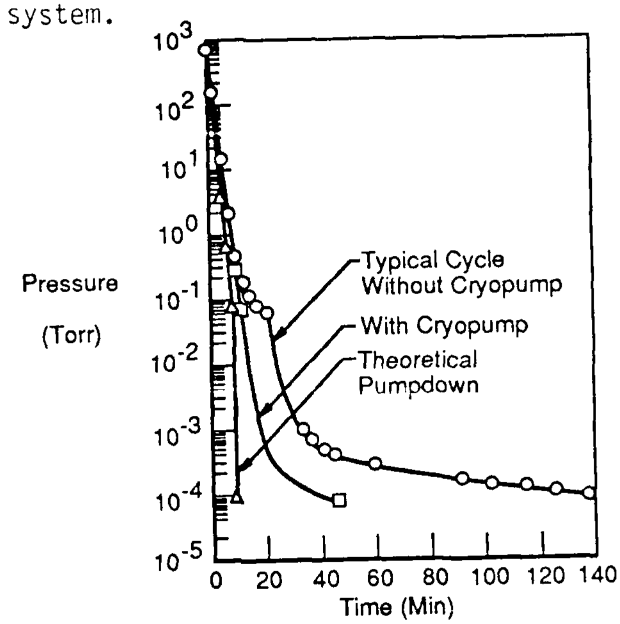


Figure 54. Effect of Cryopump on Pumpdown Times.

The above improvements translate directly into cost reductions for IVD aluminum processing. They are recommended for both existing and future ALC coating operations. However, these productivity improvements have yet to be experienced extensively throughout the finishing industry.

The coater cycle time for IVD aluminum in our cost comparison example, for instance, is 210 minutes. This time reflects the need to pumpdown the coater (45 minutes) and coat the 36 x 12 x 8 inch details once, and then to open the coater, turn the parts over by hand, and repeat the pumpdown (45 minutes) and coating cycle again to obtain acceptable uniformity. The use of the rotary parts holding accessory would rotate the parts during coating, eliminating the need to open the chamber to turn the parts and eliminating a second coater pumpdown. Coater pumpdown, the longest portion of the coating cycle, is thereby reduced 50 percent. That time could then be reduced by an additional 50 percent with the use of the cryopump accessory. With the additional efficiencies of one coating cycle rather than two and the use of a cryopump, the 210 minute total cycle would be reduced to approximately 107 minutes, a 49 percent productivity improvement.

Further improvements should continue as the process becomes more of an industry standard. This bodes well for future IVD aluminum cost reductions relative to cadmium processing.

The use of IVD aluminum in place of cadmium should also provide life-cycle cost savings. These savings result from reduced maintenance, lower structural weight, and longer product life. In a study conducted for the F-18 program (Reference 88), for example, the replacement interval for IVD aluminum-coated fasteners was projected to be approximately double the interval for cadmium-plated fasteners. At the same time, reduced damage to the countersinks of the aluminum structure was projected. This would result in additional savings from lower structural refurbishment costs. Performance data substantiating these projections is presented in Section III.

In addition to longer intervals between required maintenance, there is also cost savings associated with the overhaul procedures themselves when IVD aluminum rather than cadmium processing is involved. As pointed out in Section IX(E), the stripping of cadmium-plated parts during refurbishment produces hazardous wastes and results in additional collection and disposal costs. In contrast, there are no hazardous waste problems or cost associated with the removal of aluminum coatings during refurbishment.

The use of IVD aluminum in place of anodize coatings on fatigue-critical aluminum structure reduces the weight or increases the life of these structures; see Section VI(A) for technical details. These benefits translate into life-cycle cost savings by reducing aircraft size and related operating costs or by reducing the necessity to replace structural components. Cadmium is not an acceptable alternative for this application.

In summary, today's cost of IVD aluminum processing is competitive, if not less expensive, then cadmium processing. At the same time, the total cost of cadmium processing is increasing rapidly as the finishing industry facilitizes and changes procedures to control hazardous waste production and meet health-related laws and regulations. Conversely, the cost of IVD aluminum processing is being reduced as a result of productivity improvements associated with its expanding usage. IVD aluminum offers advantages regarding life-cycle costs as well. Therefore, cost consideration should in no way impede the substitution of IVD aluminum for cadmium. In fact, cost consideration, similar to technical performance and environmental or health considerations, provides an additional incentive to substitute IVD aluminum processing for cadmium processing.

SECTION IX

ENVIRONMENTAL IMPACT

The functional merits of IVD aluminum versus cadmium processing have been thoroughly discussed in other sections of this report. However, the most important reason for replacing cadmium with IVD aluminum at the ALCs may be found in an examination of how the two metals and their respective processing procedures impact upon the environment.

Both aluminum and cadmium as metallic finishes require a similar processing sequence of precleaning, coating or plating, and postcoat processing. Because must of the precleaning and post-coat processing steps are common to both finishes, it is the nature of the two metals and the actual plating or coating process that exhibits most of their environmental impact differences. Aluminum is a nontoxic substance, and the IVD vacuum-coating process is a dry, environmentally clean process. Cadmium, on the other hand, is classified as toxic to humans; waste cadmium must be handled and disposed of by approved Occupational Safety and Health Administration (OSHA) and Environmental Protection Agency (EPA) procedures. In addition, electroplated cadmium processing introduces additional hazardous waste materials, such as cyanide in the plating bath, which must be controlled.

A. PRECLEANING

The IVD aluminum and the various cadmium processes require part precleaning prior to application of the finish. These part precleaning processes for alloy steel parts are shown in Table 34. Precleaning basically consists of:

- Solvent cleaning to remove organic contaminants from the part surface such as grease and oil films, cutting fluids, and corrosion prevention compounds.

- Chemical or mechanical cleaning to remove surface oxides.

TABLE 34. PRECLEANING REQUIREMENTS.

Proesss	Solvents	Chemicals	Others
IVD Aluminum	Alcohol Acetone MEK Chlorinated Solvents[a]	None	Abrasive (Al_2O_3 & Air)
Vacuum Cadmium	Alcohol Acetone MEK Chlorinated Solvents[a]	None	Abrasive (Al_2O_3 & Air)
Electroplated Cadmium Nickel-Cadmium	Alcohol Acetone MEK Chlorinated Solvents[a]	Sodium Cyanide (Option) Sodium Hydroxide Hydrochloric Acid (20°Be)	None
Low-Embrittlement Cadmium	Alcohol Acetone MEK Chlorinated Solvents[a]	None	Abrasive (Al_2O_3 & Air)

Key:
a 1, 1, 1 Trichloroethane
Trichloroethylene
Perchloroethylene

Vapor degreasing is the most common solvent cleaning process and is generally used with either IVD aluminum or cadmium processing. Vapor degreasers use a chlorinated solvent as the cleaning agent. Various regulatory agencies have determined that chlorinated solvents contribute varying degrees of harm to a worker's health and the environment (ozone layer and ground water). Both IVD aluminum and cadmium processing allow the use of 1, 1, 1, Trichloroethane which has higher acceptable OSHA vapor exposure limits than some of the commonly used solvents and is exempt from air pollution regulations in most states.

For the application of IVD aluminum, alloy steel parts are required to be mechanically cleaned after solvent cleaning. Surface oxides are abrasively removed by a process that requires clean dry air and aluminum oxide (Al_2O_3) grit. This dry process is nontoxic and has no environmental impact.

The cadmium processes used for high-strength steel applications, vacuum cadmium and low-embrittlement cadmium, normally specify the part to be mechanically cleaned also. This is because chemical precleaning can cause hydrogen embrittlement of high-strength steel. However, the lower alloy steel parts which are "bright" cadmium- and diffused nickel-cadmium-plated are normally chemically cleaned. Materials such as sodium cyanide (an optional desmutting step) in the chemical cleaning process are toxic and require special handling and disposal procedures.

B. COATING/PLATING

The materials required for the processing of IVD aluminum, vacuum cadmium, electroplated cadmium, diffused nickel-cadmium, and low-embrittlement cadmium are given in Table 35.

TABLE 35. COATING/PLATING REQUIREMENTS.

Process	Chemicals or Compounds
IVD Aluminum	Aluminum
Vacuum Cadmium	Cadmium
Electroplated Cadmium Low Embrittlement Cadmium Nickel-Cadmium Diffused	Sodium Cyanide Sodium Hydroxide Cadmium Oxide Sodium Carbonate
Electroplated Nickel (For Diffused Nickel-Cadmium)	Nickel Sulfate

IVD aluminum and vacuum cadmium processing does not require any outside chemicals or compounds. Both processes utilize environmentally clean vacuum evaporation to apply the coating to the substrate. Figure 55 shows a typical IVD aluminum work area. The environmental difference between the two is that aluminum is a nontoxic element. Cadmium is a heavy metal and is toxic to humans. Cadmium fumes or dust breathed or ingested by humans can cause

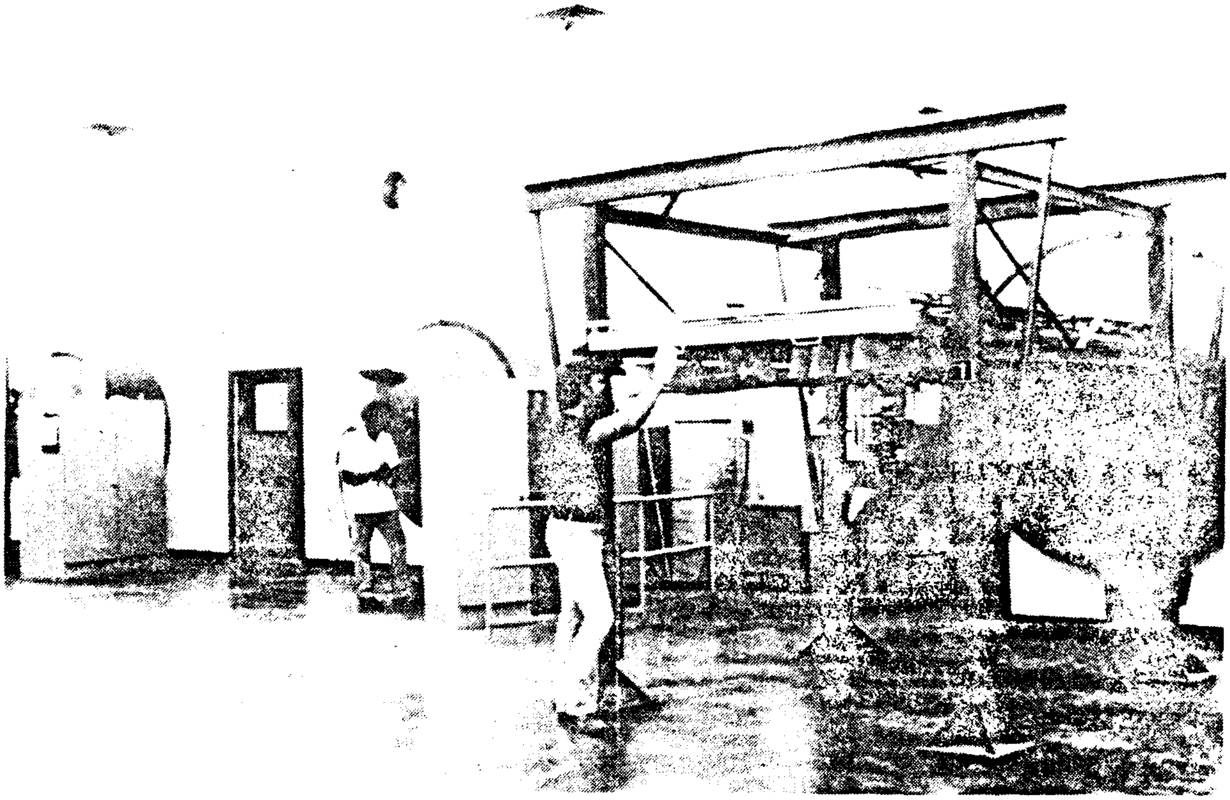


Figure 55. IVD Aluminum Production Work Area.

illness and even death. Extreme care must be taken when cleaning excess cadmium buildup from the interior surfaces of the vacuum coating chambers due to the potential health hazards from the cadmium dust. Even brief exposure to high concentrations have been known to result in pulmonary edema and death (Reference 89). These symptoms are usually delayed for some hours after exposure and fatal concentrations may be breathed without sufficient discomfort to warn the worker to leave the exposure. TRW performed a study(*) for the Ogden ALC and issued a report in which they stated:

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*Shehan, D. J., Modernization Plan Section of the Final Report on Modernization of the USAF Landing Gear Technical Repair Center (TRC), Letter No. 0411.18.83-001 from Defense and Space Systems Group of TRW Inc., 27 January 1983.

"Possibly the most important reason for increasing the use of IVD in the landing gear technical repair center is the initial reduction and subsequent elimination of highly toxic cadmium systems used in MAN. After modification of the existing IVD system and the procurement of a new IVD system, one half of the present vacuum cadmium workload could be processed by aluminum IVD. After operators become familiar with the operation and capabilities of the new equipment, the remaining fifty per cent of the vacuum cadmium workload could be processed by IVD, thus eliminating the hazardous cadmium vapors."

The cadmium processes involving electroplating, "bright" cadmium, low-embrittlement cadmium, and diffused nickel-cadmium, require the use of plating solutions that are cyanide based to generate the cadmium finish. Cyanide is highly toxic to humans and animal life, and care must be taken in the handling and use of this material. A typical electroplated cadmium work area is shown in Figure 56. Processing with chemical solutions can be safe if proper procedures are followed. If an acid accidentally comes into contact with

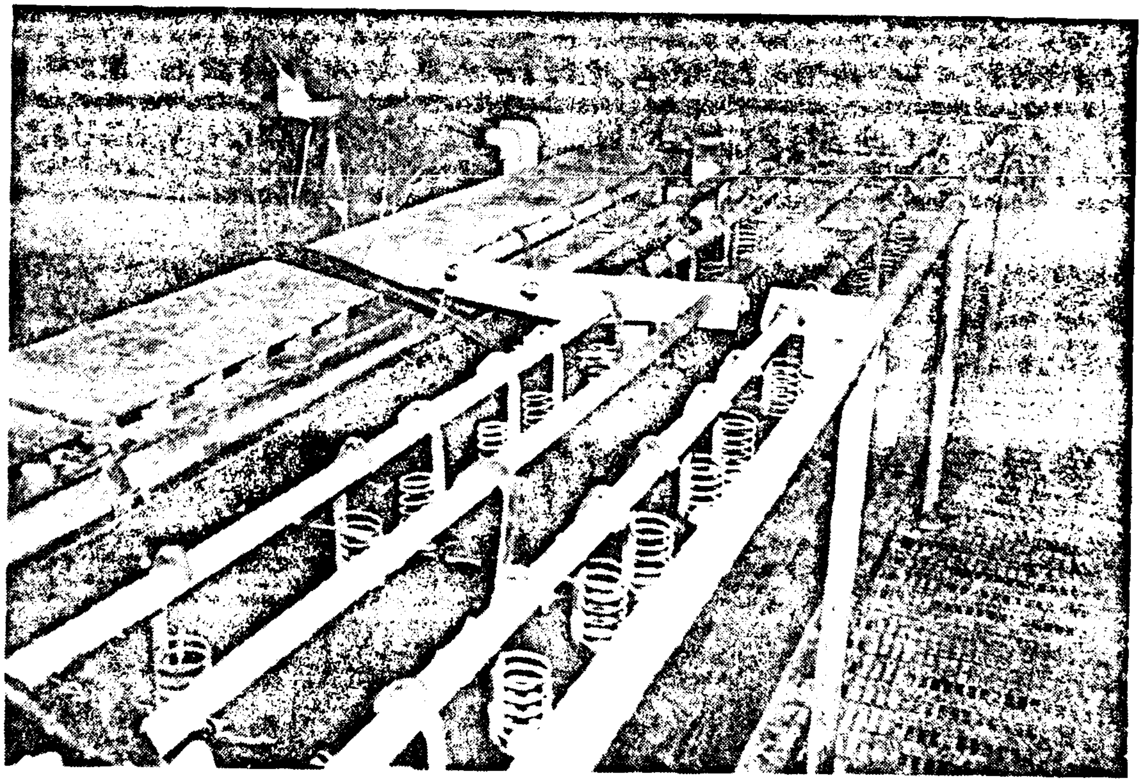

Figure 56. Typical Electroplated Cadmium Work Area.

cyanide, however, deadly hydrogen cyanide gas is generated. Since acids are commonly used for precleaning in most plating facilities, the potential exists for accidental mixing.

The use of electroplated nickel in the nickel-cadmium process involves an additional hazardous material, nickel sulfamate. It decomposes when heated and emits toxic fumes consisting of the oxides of nitrogen (NO_x) and sulfur (SO_x). This compound requires special handling and storage procedures to prevent the generation of toxic fumes in the work place.

Waste disposal is a major problem for the cadmium processes but not for the IVD aluminum process. Treatment of cadmium plating solutions and rinsewaters is required. This is usually a two step process requiring the destruction of cyanide followed by precipitation of the cadmium. Both steps require separate tanks, instrumentation, chemicals, and man-hours. The cyanide destruction is generally performed by the alkaline chlorination-oxidation process. This process is a two-stage operation in which the cyanide is first converted to a cyanate and then the cyanate is oxidized to carbon dioxide (usually as sodium bicarbonate) and nitrogen. Sodium hydroxide is used with a chlorine source to maintain the pH of the solution at the proper levels in order for the oxidation reactions to occur.

The effluent from these processes can be diluted or buffered to obtain a safe liquid that can be dumped in a drain with no further treatment after the filtration of the precipitated cadmium compound. This remaining hazardous sludge must be dried and disposed of in a hazardous waste disposal site. Even then, the environmental impact problems have not ended. Cadmium can be extremely hazardous if it gets into the ground water system; the allowable concentration in waste water is only one-fifth that for arsenic. As a result of these problems and the associated liability, disposal costs are high and are continuing to rise. Land disposal of cadmium may be banned in the near future.

C. POSTCOAT PROCESSING

The postcoat processing steps for both IVD aluminum and the various cadmium processes are essentially the same. Both use a chromate conversion treatment which provides additional corrosion protection and a base for subsequent paint adhesion. The use of chromates is under scrutiny by regulatory agencies because of the possibility that lung cancer may be caused by hexavalent chrome and ground water pollution from trivalent chrome. The main concern with the chrome compounds is with inhalation of dust or powders.

The chromate conversion process can be a closed-loop system which limits the amount of waste products. To reduce the possibility of pollution even further, processes involving nonpolluting materials such as zirconium are being evaluated as potential replacements for chromate conversion coatings. Further research and development is recommended to find a replacement conversion coating that is environmentally acceptable and has no detrimental effect on the other coating properties; see Section XII(E).

D. OSHA STANDARDS

Cadmium processers must comply with OSHA Standards as well as EPA regulations. Inhaling small quantities of cadmium dust or fumes may cause a dry throat, cough, headache, shortness of breath, and vomiting. More severe exposure could result in death. OSHA is in the process of developing standards for the levels and monitoring of cadmium in the work place(*). OSHA has proposed a personal exposure limit (PEL) of 5 micrograms of cadmium per cubic meter as an average over 8 hours. Levels as low as 1 microgram per cubic meter as an average, over 8 hours, are proposed to be classified as action levels. Medical surveillance would be required for all exposures at or above action levels. Warning signs and step by step training would be required. Initial representative monitoring would be performed upon every full shift employee in each job classification and work area within 120 days.

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*Proposed Code of Federal Regulations, 29CFR1910.1027.

Regulated areas would be established for concentrations above the PEL. Processers would be required to have a written plan to deal with emergencies including a change room with showers for exposures above the PEL. Private industry and ALCs alike will be required to meet these stringent regulations which will be an added cost to cadmium processing. The use of cyanide solutions in the cadmium plating process also has an impact on the safety in the work area. As previously outlined, a toxic gas would be generated if an acid was inadvertently added to a cyanide solution. The present OSHA standard has a threshold limit value (TLV) of 10 PPM in air and the Department of Transportation requires labelling to state "Poison A, Poison Gas and Flammable" on all shipments of cyanide concentrate.

Conversely, aluminum is nontoxic and is safe to handle, store, and dispose of with standard shop practices. There are no OSHA Standards regulating the use of aluminum either as structural components or in its pure form as a protective coating.

E. PAINT STRIPPING

Cadmium and aluminum are both soft metals and as such may mix with solutions or blast media used to strip paint from finished parts. The environmental difference once again is in the nature of the metals. The cadmium-contaminated stripping solution or blast media is required to be disposed of as hazardous waste. Proposed OSHA PELs for cadmium, previously discussed, may well limit the effectiveness of the newer blast media paint stripping procedures. Unacceptable limits of cadmium have been found in the blast media at the Ogden ALC. The source of the cadmium is primarily from cadmium-plated alloy steel fasteners installed in aluminum alloy structure. The replacement of cadmium with IVD aluminum would eventually eliminate this environmental concern.

In summary, the use of IVD aluminum to replace the various cadmium processes would provide an acceptable way to improved the product while eliminating all environmental problems associated with the use of cadmium without introducing new ones. Aluminum is not a hazardous material. The process does not require chemical solutions, tanks, special ventilation, or rinsewater. It produces no hazardous wastes and, therefore, requires no waste treatment facilities.

As discussed in Section VIII, IVD aluminum costs are decreasing with improved coater throughput while the cost of processing with cadmium continues to increase because of environmental concerns. Pollution control and hazardous waste disposal associated with the various cadmium processes is now costing the ALCs millions of dollars each year. These costs will continue to rise as more stringent EPA and OSHA Standards are enacted. "Cradle to Grave" legislation will continue to make the ALCs responsible for any cleanup and liable for both past and present waste disposal. For these reasons, some of the ALCs have procured IVD aluminum coating equipment and aerospace and other manufacturers have been converting from cadmium processing to IVD aluminum. This change over will accelerate as more emphasis to eliminate hazardous waste is brought to bear on the processors. As examples, McDonnell Douglas Corporation has continually increased its use of IVD aluminum with a corresponding decrease in the use of cadmium finishes, and General Dynamics, Fort Worth, is bringing their first IVD aluminum installation in-house with the goal to replace cadmium processing.

Table 36 summarizes the environmental impact of the IVD aluminum process and the various cadmium processes.

TABLE 36. ENVIROMENTAL IMPACT OF IVD ALUMINUM AND CADMIUM PROCESSING.

Process	Process Sequence		
	Preclean	Coating/Plating	Post-Coat
IVD Aluminum	None	None	T, P, H
Electroplated Cadmium	P, H	T, P, O, H	T, P, H
Low Embrittlement Cadmium	None	T, P, O, H	T, P, H
Diffused Nickel-Cadmium	T, P, H	T, P, O, H	T P, H
Vacuum Cadmium	None	T, O, H	T, P, H

Key
T – Toxic materials
P – Polution control required
O – OSHA standards imposed
H – Hazardous waste disposal

SECTION X

DATA GENERATED DURING CONTRACT PERIOD

During the Phase I contract period, MCAIR generated corrosion resistance data from "typical" ALC details that were coated with IVD aluminum. Data is presented on parts that were coated and tested by MCAIR as well as details that were coated and tested by the Oklahoma City ALC. MCAIR also reviewed ALC details that are now processed with cadmium to determine the approximate percent of those that can be easily changed to IVD aluminum without concern as opposed to those presenting an "area of concern." Research and development will be directed at "areas of concern" during Phase II. MCAIR also tested IVD aluminum-coated coupons to demonstrate the generic nature of the coating as presented in Sections II through VII.

A. CORROSION RESISTANCE TESTING OF ALC DETAILS

1. By MCAIR

MCAIR coated 15 scrapped (condemned) ALC production parts (Table 37) received from the San Antonio and Oklahoma City ALCs with IVD aluminum and tested their corrosion resistance. The parts were coated with IVD aluminum to the requirements of Mil-C-83488 (Coating, Aluminum, High Purity) in the MCAIR production facility. A Class 1 (one mil minimum) IVD aluminum coating was applied to all parts except in the threaded areas. The threaded area of a part received a Class 3 coating, nominally 0.3-0.5 mils. Parts having recesses or internal surfaces were coated using standard MCAIR procedures, such as proper part orientation, to optimize coating coverage. All of the parts were chromate conversion-coated to produce a Type II coating. Figure 57 is typical of the appearance of a properly processed part. The 20-inch diameter Case and Vane Assembly has been IVD aluminum-coated, glass-bead-peened for coating adhesion verification, and chromate conversion-coated. Coating thicknesses for the various details is shown in Table 37.

TABLE 37. NEUTRAL SALT FOG TEST RESULTS FOR IVD ALUMINUM-COATED, TYPICAL ALC PARTS AT MCAIR.

Part Number	Part Name	Average Coating Thickness (mils)	Test Duration (Days)	Remarks
AN 103812	Bolt	Faces of Hexagon Head 1.6 Top of Head 1.3 Threads ~0.45	28 67	Coating appearance is excellent. Coating appearance is good. Some coating depletion has occurred on two faces of the hexagonal bolt head. Rust has not occurred.
6735892	Double Bracket	Top Side 1.1 Bottom Side 1.4	28 67	Coating appearance is excellent. Coating appearance is very good. Coating depletion is starting at two spots on the edges. Rust has not occurred.
6709768	Washer	External Surfaces ~2.3	28 67	Coating appearance is excellent. Coating appearance is very good. Coating depletion is starting on some lands at the corners. Rust has not occurred.
6723224	Nut	External Surfaces ~2.3	28 67	Coating appearance is excellent. Coating appearance is very good. Minor coating depletion is starting at three spots. Rust has not occurred.
6819694	Bolt	External Surfaces ~2.3 Threads ~0.45	28 67	Coating appearance is very good. Minor coating depletion is starting on the O.D. and in the I.D. recess. Coating appearance is fair to good. Coating depletion is occurring at several spots on the O.D. The I.D. is showing considerable coating depletion. Rust has not occurred.
6826935	Arm, Power Control	External Surfaces ~2.3	28 67	Coating appearance is very good. Minor coating depletion is occurring in one area. Coating appearance is good. Some coating depletion is occurring at three spots. Rust has not occurred.
359439	Seat Turbine Shaft Coupling Lock Spring	Top Edge 1.4 I.D. Center 1.8 O.D. Center 2.2	28 67	Coating appearance is fair to good. Part showed early coating depletion in one area on the O.D. I.D. showed no coating depletion. Coating appearance is fair to poor. There is a large area over which coating depletion is occurring on the O.D. On the I.D. there is coating depletion along part of the rim of the part. Rust has not occurred.

TABLE 37. NEUTRAL SALT FOG TEST RESULTS FOR IVD ALUMINUM-COATED, TYPICAL ALC PARTS AT MCAIR (CONTINUED).

Part Number	Part Name	Average Coating Thickness (mils)	Test Duration (Days)	Remarks
201616	Collar, Front Compressor (Split Into Two Havles)			
	O.D. Test Section	Top Edge 1.4 O.D. Center 2.0	28	Coating appearance is fair to good. Part showed early coating depletion in two areas on the O.D.
			64	Coating appearance is poor. There are two large areas over which coating depletion is occurring. Rust has not occurred.
	I.D. Test Section	Top Edge 1.4 I.D. Top Half 1.0 I.D. Bottom Half 1.2	28	Coating appearance is very good. There is one minor spot starting to show coating depletion.
			64	Coating appearance is good. There are four small spots over which coating depletion is occurring. Rust has not occurred.
6859604	Compressor Vane	Blade Side Convex 1.4 Concave 1.2 Outer Ring O.D. 2.0 Inner-Ring I.D. 1.7	28	Coating appearance is fair to good. Some coating depletion is occurring at assembled faying surfaces on the compressor vane inner-ring I.D.
			63	Coating appearance is poor. The coating on the inner-ring I.D. is almost totally depleted due to the coating sacrificing to the assembled faying surfaces. The coating on the blades is also sacrificing to the faying surfaces to protect them from corrosion. Rust has not occurred.
6859606	Compressor Vane	Blade Side Convex 1.4 Concave 0.9 Outer Ring O.D. 2.1 Inner-Ring I.D. 1.7	28	Coating appearance is good. Some coating depletion is occurring at faying surfaces on the compressor vane inner-ring I.D.
			63	Coating appearance is fair. The coating on the inner-ring I.D. is partially depleted due to the coating sacrificing to the faying surfaces. The coating on the blades is also beginning to sacrifice to the faying surfaces to protect them from corrosion. Rust has not occurred.

TABLE 37. NEUTRAL SALT FOG TEST RESULTS FOR IVD ALUMINUM-COATED, TYPICAL ALC PARTS AT MCAIR (CONTINUED).

Part Number	Part Name	Average Coating Thickness (mils)		Test Duration (Days)	Remarks
2173320	Case and Vane Assembly	Blade/Side Convex Concave	 1.0 0.7	28	Coating appearance is good. There is some coating depletion at the faying surface in a recess adjacent to the inner-ring O.D.
				63	Coating appearance is fair. The coating in a recess adjacent to the inner-ring O.D. is partially depleted due to the coating sacrificing to the faying surfaces. The coating on the blades is also beginning to sacrifice to the faying surfaces to protect the faying surfaces from corrosion. The O.D. of the outer ring is showing some coating depletion at the blade attachment points. Rust has not occurred.
247346	Coupling, Front Compressor Drive Turbine (Longer Part) (Split Into Two Halves)				
	I.D. Test	At Center of I.D. Gear Teeth	 0.4	14	Coating appearance is fair to good on the I.D. The coating passed the Class 3, Type II requirement. The coating is depleting at several spots on the I.D. gear teeth.
				17	The depleted area on the I.D. gear teeth began to show rust.
	O.D. Test	O.D. Wall	1.0	14	Coating appearance is good. Some coating depletion is occurring adjacent to the area on the I.D. that showed coating depletion.
				28	The coating appearance is fair. The coating is depleting adjacent to the cut edge of the part. The early depletion area on the O.D. is thought to have occurred from the coating sacrificing itself to help protect the depleted area on the I.D. Rust has not occurred.
6841212	Wheel, Compressor 2nd Stage	Top Bottom	1.6 0.9	28	Coating appearance is excellent. There is one spot showing some coating depletion. The test will continue until failure occurs.
6792768	Wheel, Compressor 8th Stage	Top Bottom	1.4 1.0	28	Coating appearance is very good. There are a few spots on the O.D. lands between blade installation slots that show some coating depletion starting. The test will continue until failure occurs.

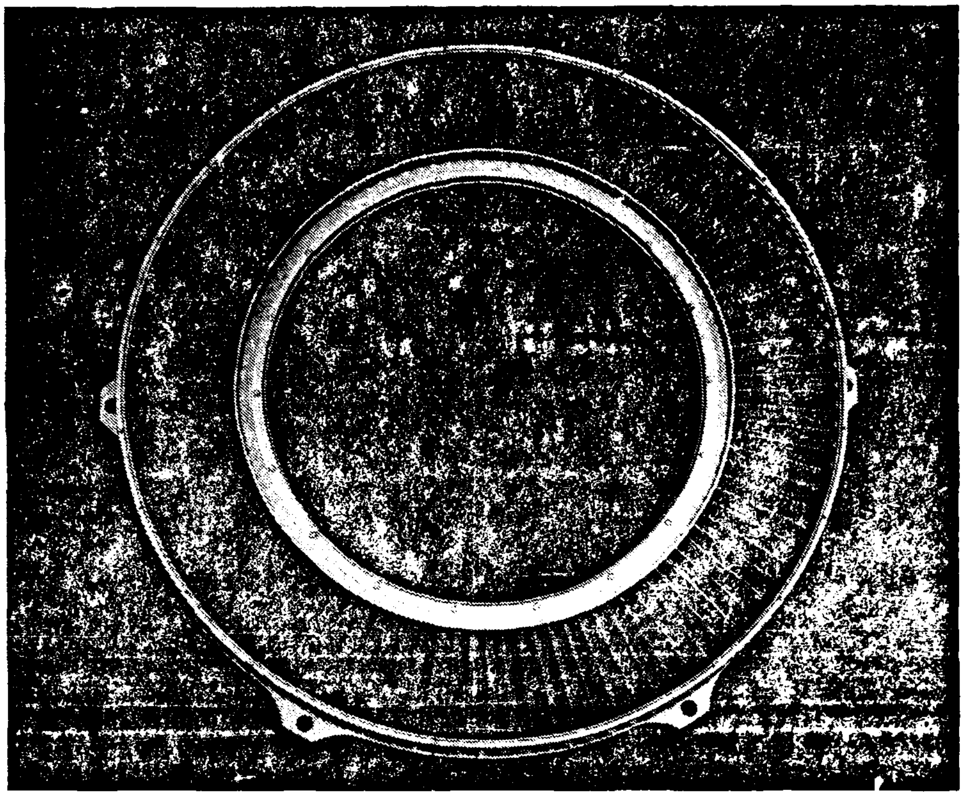
TABLE 37. NEUTRAL SALT FOG TEST RESULTS FOR IVD ALUMINUM-COATED, TYPICAL ALC PARTS AT MCAIR (CONCLUDED).

Part Number	Part Name	Average Coating Thickness (mils)	Test Duration (Days)	Remarks
247346	Coupling, Front Compressor Drive Turbine (Shorter Part) (Split Into Two Halves)			
	I.D. Test	I.D. Gear Teeth 0.5	14	Coating appearance is good. The coating passed the Class 3, Type II requirement. The coating is depleting at several spots on the I.D. gear teeth. The test will continue until failure occurs.
	O.D. Test	O.D. Wall 1.0	14	Coating appearance is excellent. There is no coating depletion on the O.D. The test will continue until failure occurs.

Note:

1. The MIL-C-83488 corrosion resistance requirement is 672 hours (28 days) for Class 1 coatings (1.0 mil minimum) and 336 hours (14 days) for Class 3 coatings (0.3 mil minimum).

Top



Bottom

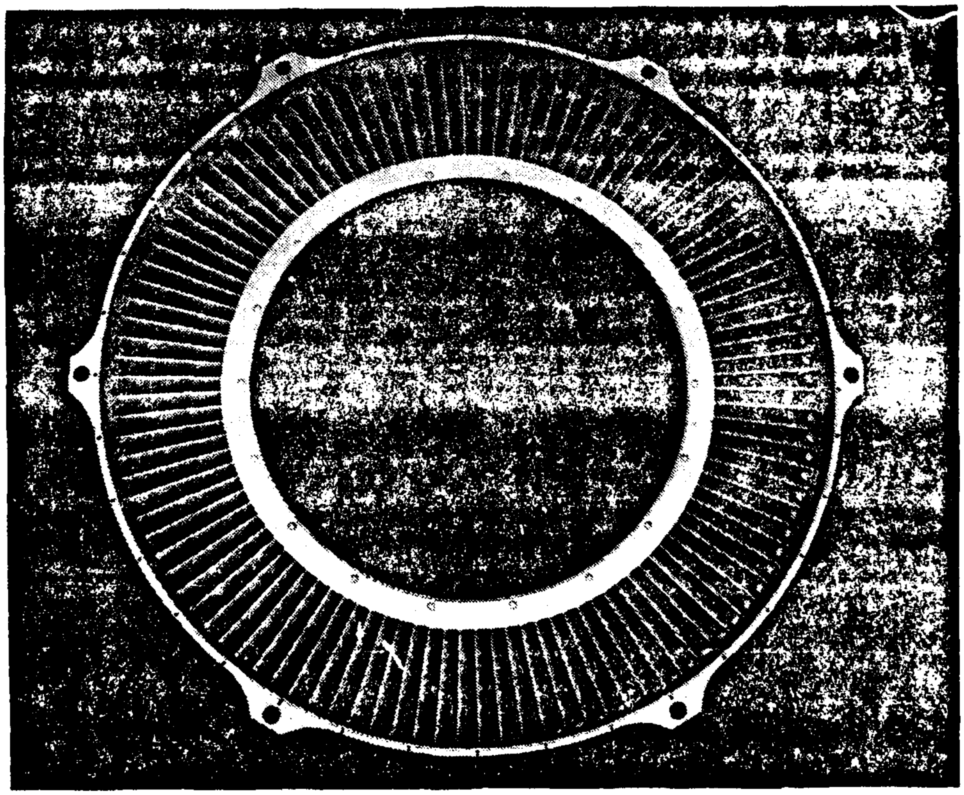


Figure 57. IVD Aluminum-Coated Case and Vane Assembly (P/N 2173320).

The IVD aluminum-coated parts were exposed to an ASTM B-117 neutral salt fog environment until failure occurred (substrate corrosion) or until the testing was terminated. All of the parts passed MIL-C-83488 salt fog exposure times which are 14 days for Class 3 coatings and 28 days for Class 1 coatings. Figures 58 through 60 shows several of the parts after 672 hours of exposure. Table 37 gives a verbal description of the parts beginning with either 14 days or 28 days of exposure.

Substitution of IVD aluminum for cadmium provided the required corrosion protection to 15 typical ALC parts. This task demonstrates that the majority of the ALC parts can be coated with IVD aluminum without sacrificing coating quality or performance. Parts having "areas of concern" will be addressed in future research and development as noted in Section XII.

1. By the Oklahoma City ALC

The Oklahoma City ALC (OC-ALC) has approved IVD aluminum coating by demonstrating the corrosion resistance adequacy and process feasibility on some of their production details that are now finished with either cadmium or nickel-cadmium. Twenty-four ALC details were coated with IVD aluminum to MIL-C-83488, Type II (chromated). The coating thicknesses are shown in Table 38. Seventeen of the same ALC details were plated with diffused nickel-cadmium for direct comparisons. The nickel-cadmium plated parts were processed as follows:

Nickel plate - 0.0002 to 0.0004 in. thick
Cadmium plate - 0.0001 to 0.0002 in. thick
Supplemental chromate treatment - optional

All of the details were exposed to an ASTM B-117 neutral salt fog environment until failure occurred (substrate corrosion) or until termination of the test. Salt fog duration times and remarks about the appearance of the parts are presented in Table 38. Table 38 also shows a comparison between IVD aluminum, nickel-cadmium, and Sermetel for one OC-ALC part. The coating thickness/surface roughness characteristic for three OC-ALC parts is shown in Table 39.

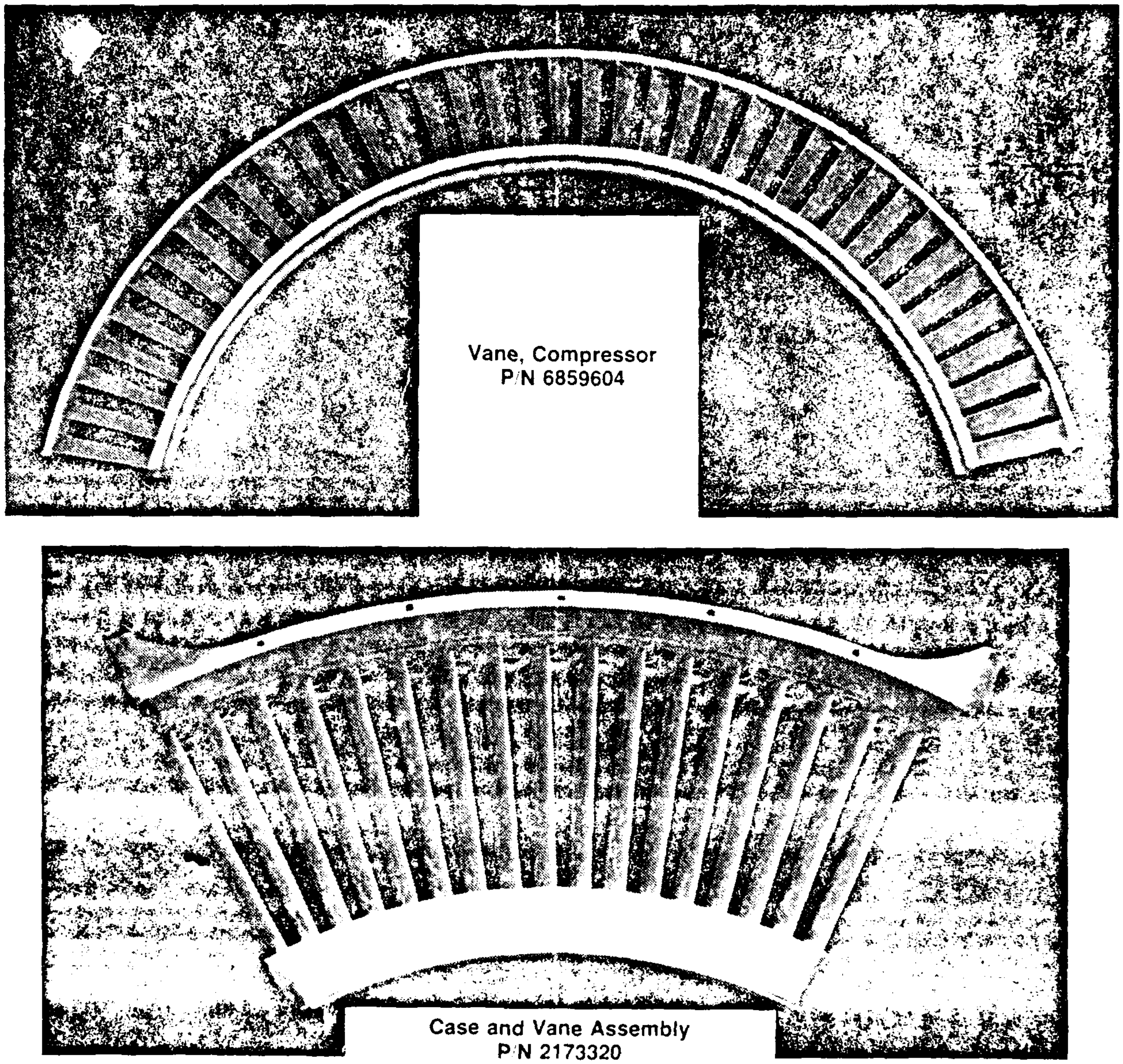
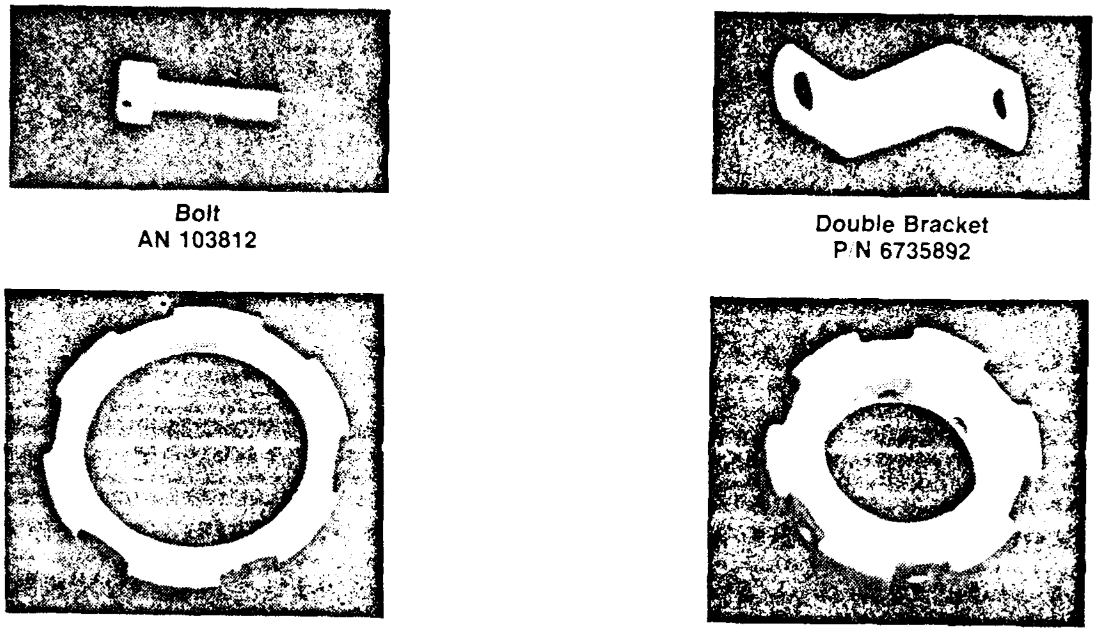


Figure 58. IVD Aluminum-Coated Engine Sections After 672 Hours of Neutral Salt Fog Exposure.



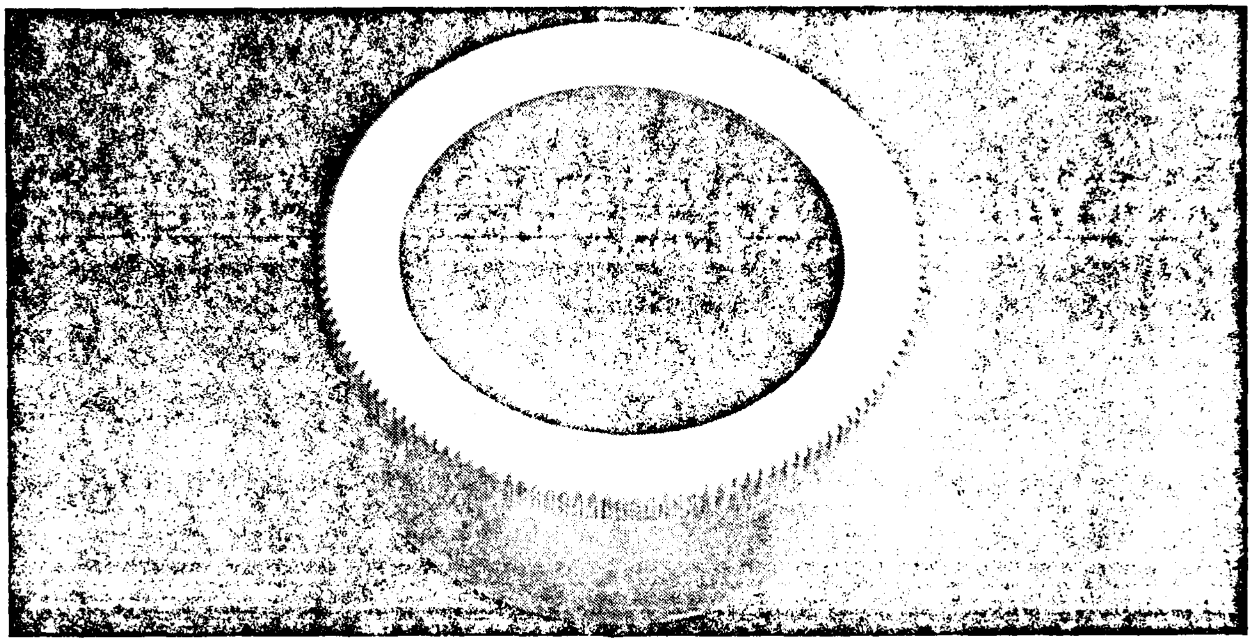
Bolt
AN 103812

Double Bracket
P/N 6735892

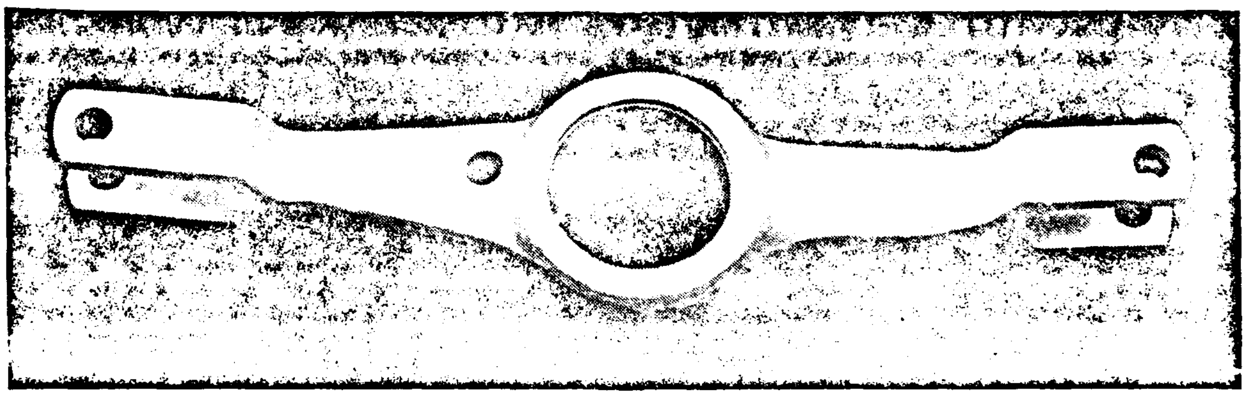
Nut
P N 6723224

Washer
P N 6709768

Figure 59. IVD Aluminum-Coated Small ALC Parts After 672 Hours of Neutral Salt Fog Exposure.



Seat Turbine Shaft Coupling
Lock Spring
P/N 359439



Arm, Power Control
P/N 6826935

Figure 60. IVD Aluminum-Coated ALC Parts After 672 Hours of Neutral Salt Fog Exposure.

TABLE 38. NEUTRAL SALT FOG TEST RESULTS COMPARING IVD ALUMINUM- AND NICKEL-CADMIUM-FINISHED PARTS AT THE OKLAHOMA CITY ALC.

Engine Number	Part Number	Part Name	Average Aluminum Coating Thickness (mils)	Coating	Test Duration (Days)	Remarks
30531R	559378	Tierod Bolts, Front Compressor	1.3	IVD Al	92	Pits Forming but No Rust
				Ni-Cd	48	Small Amount of Rust on Threads and Head
			—	IVD Al	92	Pits Forming but No Rust
				Ni-Cd	23	Small Rust Spot Forming – Entire Length
33354R or 57369Y	157532	Ring-Retaining L S Compressor	1.4	IVD Al	102	No Rust
				IVD Al	92	No Rust
				Ni-Cd	66	Rust Beginning to Form
33350R	359439	Lock, Front Compressor Turbine	1.4	IVD Al	102	No Breaks in Coating or Rust
				Ni-Cd	10	Severe Rust
				IVD Al	160	Remains in Cabinet, Good Condition
				Ni-Cd	8	Severe Rust – Began After Two Days
Note: Ni-Cd plating on parts above was noted to be nonuniform with white spots.						
33348Y or 57372Y	208178	Spring, Front Compressor Turbine	1.4	IVD Al	55	Some Discoloration, No Breaks
				Ni-Cd	99	Dark Area on One End – No Rust.
33897Y or 57723Y or 057723	403326 308892 277092 178124 403327	Nut Assembly, Accessory Drive Pad	O.D. 1.3 I.D. 0.5	IVD Al	26	Rust on Internal Surfaces, Around Nut
				Ni-Cd	6	Rust on Internal Surfaces, Around Nut
57670Y or 57743Y or 33511UY or 57479N & Y	334974	Water Injet Screen	1.3	IVD Al	55	No Breaks
				Ni-Cd	14	Small Rust Spots on Screen
30737Y	502178	Housing, Bearing, Inner Gearbox	Face 0.9 Recess 0.3	IVD Al	26	Rust
30737G			Face 1.5 Recess 0.5	IVD Al	53	Pits Beginning, No Rust
30723G	502184			Ni-Cd	14	Rust
41763R	6865326	Link Bell Crank Assembly	1.4	IVD Al	30	Rust
30670R	510790	Large Bracket	1.3	IVD Al	55	No Breaks or Rust
				Ni-Cd	15	One Large Rust Spot – Bend

TABLE 38. NEUTRAL SALT FOG TEST RESULTS COMPARING IVD ALUMINUM- AND NICKEL-CADMIUM-FINISHED PARTS AT THE OKLAHOMA CITY ALC (CONTINUED).

Engine Number	Part Number	Part Name	Average Aluminum Coating Thickness (mils)	Coating	Test Duration (Days)	Remarks
33670	464162	Sort Items				
		Plate	1.4	IVD Al	30	Rust Forming
		Small Bracket	1.4	IVD Al	96	Two Small Breaks in Coating
				Ni-Cd	61	Small Rust Spot, Surface Black
		Fitting	1.4	IVD Al	117	Small Rust Spot
				Ni-Cd	154	Several Small Rust Spots
41900R	6861241	Regulator Air Flow Control	O.D. 1.8 I.D. 0.3	IVD Al	55	No Rust
30715G	739635	Housing Gearbox, Drive Bearing	O.D 0.7 – 1.0	IVD Al	53	No Rust or Discoloration
30732G	618865	Housing Assembly, Gearbox Bearing	—	IVD Al	53	Pits Beginning, No Rust
—	—	Housing, Inner Bearing		Ni-Cd	1	Red Spots on Nonplated Surfaces
—	—	Nuts and Bolts (Barreled)	—	IVD Al	41 58	Majority Removed, No Rust Last Two Removed, Rust Forming
30320X	559824	Coupling Gearbox, Drive Gear	O.D. 1.5	IVD Al	53	Rust, Began to Form After 45 Days. Rust on Internal Uncoated Surface
30320R			O.D. 1.3	IVD Al	41	No Rust or Discoloration
A00034	204104	Carrier	O.D. 1.5	IVD Al	53	Pits and Rust Beginning
				Ni-Cd	1	Rust on Nonplated Surface Al-IVD Parts Had Entire Surface Coated
30318R	565084	Tube Sealing RR Compressor	O.D 1.2 Groove 0.5	IVD Al	41	No Rust or Discoloration
33346R	247346	Coupling, Front Compressor	O.D 1.3 Inside 0.1 – 0.3 and Threaded	IVD Al	16	Rust
				Ni-Cd	29	Rust
		Test Strips Four With Alodine One Without Alodine	2.0	IVD Al	140	Some With Dark Areas and Breaks in the Coating and Pits Beginning to Form
33348Y	359439 364827 714165	Seat, Turbine Shaft Coupling	O.D. 1.6 I.D. 1.0 Recess 0.1 – 0.3	IVD Al	41	Breaks in Coating, Gray Surface
				Ni-Cd	8	Rust on 1/4 of Internal Surface

**A COMPLETE COPY IS BEING SENT UNDER SEPARATE COVER. YOU SHOULD RECEIVE IT IN A COUPLE DAYS. (INSURANCE IF YOU CAN'T READ THIS COPY)

Mary Reynolds

TABLE 38. NEUTRAL SALT FOG TEST RESULTS COMPARING IVD ALUMINUM- AND NICKEL-CADMIUM-FINISHED PARTS AT THE OKLAHOMA CITY ALC (CONCLUDED).

Engine Number	Part Number	Part Name	Average Aluminum Coating Thickness (mils)	Coating	Test Duration (Days)	Remarks
—	TF30	Stator	Face 1.5 Ring 1.0 Blade 0.5 – 1.6 Recess 0.3 – 0.5	IVD Al	27	Pits and Rust Forming/Black Spots, Breaks in Coating After 17 Days
				Ni-Cd	28	Numerous Small Rust Spots on Outer Ring – in Much Better Condition Than Al-IVD After 27 Days
—	500756	Bracket, Ignition Exciter	1.6	IVD Al	41	Small Breaks In Coating/Gray Areas
				Ni-Cd	41	Marbled Area - Galvanic Reaction With Aluminum Masking Tape
—	739635B	AB Cylinder	1.0 – 1.5	IVD Al	41	Breaks In Coating 1/10 of Surface
				Sermetel	41	Dark Gray Spots Over Most of Surface
				Ni-Cd	72	Extensive Marbled Area – Galvanic Reaction With Aluminum Masking Tape. Small Rust Spots

Notes:

1. Nickel-Cadmium plating per AMS 2416
   Nickel plate – 0.0002 to 0.0004 in. thick
   Cadmium plate – 0.0001 to 0.0002 in. thick
2. The MIL-C-83488 corrosion resistance requirement is 672 hours (28 days) for Class 1 coatings (1.0 mil minimum) and 336 hours (14 days) for Class 3 coatings (0.3 mil minimum).

TABLE 39. IVD ALUMINUM-COATING CHARACTERIZATION BY THE OKLAHOMA CITY ALC.

Engine Number	Part Number	Part Name	Average Coating Thickness (mils)	Surface Roughness (μin.)
30531R	559378	Tierod Bolts, Front Compressor	1.3	72
33354R or 57369Y	157532	Ring-Retaining L/S Compressor Coupling	1.4	75
33350R	359439	Lock, Front Compressor Turbine	1.4	4.5

Notes:

1. Thickness was measured used Fisherscope nondestructive coating thickness gauge.
2. Surface roughness was measured by QVC laboratory

In the OC-ALC tests, there were 16 direct comparisons between IVD aluminum and nickel-cadmium. IVD aluminum equaled or exceeded the protection against corrosion provided by nickel-cadmium on 13 of 16 parts (Reference 91). The Front Compressor Coupling (P/N 247346) was one of the three parts for which nickel-cadmium provided better protection. This part has a threaded internal surface (ID) were the IVD aluminum coating thickness was less (0.1 - 0.3 mils) than the minimum coating thickness for satisfactory protection against corrosion. The sacrificial, aluminum coating was rapidly depleted and led to an early but normal failure for a part with a thin IVD aluminum coating. This particular part is an example of one "area of concern" where the length-to-diameter ratio is such that it is difficult to obtain adequate ID coverage. This part was later coated at MCAIR where it was demonstrated that a Class 3 coating (0.3 mils minimum) on the ID can be obtained as well as acceptable corrosion resistance. In another part, a TF30 stator, the corrosion resistance of nickel-cadmium barely exceeded that of aluminum (28 days versus 27 days). Again it is thought that the IVD aluminum was thin in the blade root areas and in other recesses. A section from a similar part, the Case and Vane Assemble coated at MCAIR and shown in Figures 57 and 58, has easily passed the Class 1 corrosion resistance requirement of 28 days at MCAIR. In fact, this part is still in test after 63 days. It is beginning to exhibit coating depletion in recesses and in the blade root areas but has not failed. A similar coating depletion pattern was observed on the TF30 Stator tested by the OC-ALC.

All of the 24 IVD aluminum-coated parts met the corrosion resistance requirements of MIL-C-83488 during initial testing. Twenty-one of the 24 parts met the 28 day Class 1 requirement. The other three details were Class 3 coatings that met the 14 day requirement. Improvement in salt fog duration times have subsequently been shown for these three parts by increasing the coating thickness on internal surfaces or in recesses. Setting an arbitrary minimum salt fog duration goal of 28 days, the OC-ALC more than doubled the prior 26 days exposure to neutral salt fog for the Inner Gearbox Housing. Complex shaped parts with recesses and/or internal surfaces must have adequate IVD aluminum coverage in these areas for the desired corrosion resistance. As noted in the previous paragraph, the Front Compressor Coupling and TF30 Stator were coated thicker at MCAIR and were able to exceed 28 days of salt fog duration.

In conclusion, the MCAIR and the OC-ALC corrosion resistance testing of 39 "typical" ALC parts demonstrates the adequacy of IVD aluminum to provide acceptable corrosion resistance for inservice applications.

B. REVIEW OF CADMIUM-PROCESSED ALC DETAILS

MCAIR visited each of the ALCs to review the various steel details that are now finished with cadmium. In conjunction with ALC personnel, these parts were examined to determine those where IVD aluminum could replace cadmium without concern. "Area of concern" were also identified. For these applications, supplemental processing is required to be used with IVD aluminum to enable adequate replacement of the cadmium process. These "areas of concern" include adequate coverage of internal surfaces, a need for improved lubricity to meet desired torque-tension values, and a need for improved erosion resistance.

A detailed list of the parts reviewed at the ALCs is presented in Tables 40 through 44. In these tables the parts that are identified as "Problem Free" are parts that could be immediately changed to IVD aluminum coating with no known processing or operating problems. At some of the ALCs, IVD aluminum has already been approved for some parts. These parts are identified in the tables as "IVD Use Approved." Those parts that present problems with insufficient coverage, that may have potential torque-tension problems, or that may be subject to erosion of the coating are identified as "Areas of Concern." Whenever multiple part numbers exists for the same verbal descriptor for a part, typically engine components, the basis for changing all of the parts to IVD aluminum coating was based upon an examination of one or more of the similar parts.

There were 70, 156, 58, 142, and 119 parts reviewed, respectively, at the Warner Robins, Ogden, Sacramento, Oklahoma City, and San Antonio ALCs. There were 65 specific parts identified with "areas of concern" or 11.9 percent of

TABLE 40. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE WARNER ROBINS ALC.

Part Number	Part Name	IVD Substitution for Cadmium			
		Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
	C141				
69C32794	Thrust Link	X	X		
3P61553-101	Bulkhead Assy.	X	X		
3P61540-101	Thrust Link Ath Mount	X	X		
3P61558-101	Aft Engine Mount (L)	X	X		
3P61558-102	Aft Engine Mount (R)	X	X		
3P61552-101	Bracket Pylon (Female Align. Fitting Bellmouth)	X	X		
3P61591-103	Bellcrank	X	X		
756102-103	Bolt	X	X		
756101-103	Bolt	X	X		
756100-103	Bolt	X	X		
78550	Ball and Socket	X	X		
78551	Ball and Socket	X	X		
78350	Ball and Socket	X	X		
78553	Ball and Socket	X	X		
3G10202-103	Drive Assy., Bellmouth	X	X		
3G10202-104	Drive Assy., Bellmouth	X	X		
3P61610-105	Pylon E Fitting	X	X		
3P61610-107	Pylon E Fitting	X	X		
3W01020-101	Strut Assembly	X	X		
3W01021-101	Strut Assembly	X	X		
3W01020-102	Strut Assembly	X	X		
3W01021-102	Strut Assembly	X	X		
3G11520-127	Bellcrank	X	X		
3G11520-128	Bellcrank	X	X		
3F32086-103	Landing Gear Nut	X	X		
3F32087-103	Landing Gear Nut	X	X		
3G11508-109	Landing Gear Nut	X	X		
3F31009-109	Link Attach Drag Brace	X			ID
3P61551-105	Side Load Fitting	X	X		
3P61551-107	Side Load Fitting	X	X		
3P61554-101	Bulkhead	X	X		
	C130				
526385-1	Barrel	X	X		
526385-2	Barrel, Mating Part	X	X		
537034	Barrel Bolt	X	X		
537035	Barrel Bolt	X	X		
537036	Internally Relieved Extension Stud	X	X		

Key:
ID - Insufficient IVD aluminum coverage on the inside diameter of the part

TABLE 40. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE WARNER ROBINS ALC (CONCLUDED).

Part Number	Part Name	IVD Substitution for Cadmium			
		Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
	C130 (Continued)				
MS20392-5C123	Pin	X	X		
MS20392-7C111	Pin	X	X		
14711-203-1	Rocker Arm	X	X		
14711-203-2	Rocker Arm	X	X		
14711-208	Stop	X	X		
14711-209	Plunger	X	X		
14711-212	Spacer	X	X		
14711-213	Insert	X	X		
14711-217	Calibration Disc	X	X		
14711-218	—	X	X		
14711-219	Pin	X	X		
14527-219	—	X	X		
14527-224	Pin	X	X		
546419	Thrust Ring	X	X		
537297	Dome Cap	X	X		
546418	Dome Retaining Nut	X	X		
MS21250-08024	Bolt	X	X		
42F-W820	Nut	X	X		
80-388	Washer	X	X		
370484-1	Shelf Bracket	X	X		
	Miscellaneous Parts				
7032192-10	Flap Outer Wing	X	X		
7032192-20	Flap Outer Wing	X	X		
370516-2R	Flap Wing Landing	X	X		
370516-2L	Flap Wing Landing	X	X		
370516-7	Flap Wing Landing	X	X		
370516-8	Flap Wing Landing	X	X		
370516-13	Flap Wing Landing	X	X		
370516-14	Flap Wing Landing	X	X		
370516-20	Flap Assembly	X	X		
370516-21	Skin Aircraft	X	X		
370516-22	Skin Aircraft	X	X		
377048-17	Flap Assembly	X	X		
377048-18	Flap Assembly	X	X		
—	Bolts and Nuts	X	X		

Key:
ID – Insufficient IVD aluminum coverage on the inside diameter of the part

TABLE 41. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE OGDEN ALC.

Part Number	Part Name	IVD Substitution for Cadmium			
		Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
	C5/C5A				
4G1436-107A	Nose Outer Cylinder	X			ID
4G13538-101	Drag Shaft	X			ID
4G11415-107A	Main Outer Cylinder	X	X	X	
4G12432-101A	Spline Tube	X	X		
4G13614-101A	Round Nut	X	X		
4G11476-107A	Positioning Collar	X	X	X	
4G11476-101A	Positioning Collar	X	X	X	
4G51427-101A	Nose Piston Axle	X			ID
4G13412-101A	MLG Collar Lock Ring	X	X	X	
4G53709-101A	Retract Arm Attach Bolt	X			ID
4G13539-101A	Main Lower Drag Shaft	X			ID
4G13586-101A	MLG Ballscrew Sprocket	X	X	X	
4G12032-107B	Main Pitch Collar Assy.	X	X	X	
4G12030-101A	Main Fwd. Axle	X			ID
4G12400-101A	Main Trunnion Pin	X	X	X	
4G12031-101A	Main Brake Collar	X	X	X	
43-761	Miscellaneous Bolts	X	X		
B15576-2R	Main Ballnut	X	X	X	
4G11439-107E	Main Roll Pin	X	X	X	
4G19067-101A	MLG Comp. Attach	X	X	X	
4G12001-101C	MLG Lower Link	X	X	X	
4G51436-107B	Outer Cylinder	X			ID
	C130				
—	MLG Inner Cylinder	X	X	X	
G41810-60	Wheel Tie Bolt	X			T-T
373587-1	MLG Inner Cylinder	X	X	X	
371675-1	Nose Cylinder Assy.	X	X	X	
388046	MLG Cylinder Assy.	X	X	X	
388072-1	NLG Fulcrum Assy.	X	X	X	
3303590-1	Nose Cylinder	X	X		
355865-1	MLG Bracket Assy.	X	X		
373587-1	MLG Inner Cylinder	X	X	X	
370440-1	MLG Inner Cylinder	X	X	X	
380236-1	NLG Brace Assy.	X	X		
337267-3	MLG Nut, Gland	X	X	X	
331258	Nut Orifice Ret.	X	X	X	
337268	MLG Bulkhead	X	X	X	
370439-3	MLG Cylinder Assy.	X	X	X	
9522014	Miscellaneous Nut	X	X		

Key:
ID – Insufficient IVD aluminum coverage on the inside diameter of the part
T-T – Torque-Tension

TABLE 41. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE OGDEN ALC (CONTINUED).

Part Number	Part Name	IVD Substitution for Cadmium			
		Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
	F-4				
762-7675-80	Inner Cylinder Assy.	X	X	X	
53G41420-3	MLG Outer Cylinder	X	X	X	
32-41672-6	Main Torque Pin	X	X	X	
32-41081-7	MLG Ring Tiedown	X	X	X	
32-41669-7	MLG Torque Arm Lower	X	X		
32-41632-5	Main Drag Brace	X	X	X	
7027675-30	MLG Inner Cylinder Assy.	X	X	X	
53-41420-301	MLG Outer Cylinder	X	X	X	
32-41675-5	Main Torque Pins	X	X	X	
7027675-70	MLG Inner Cylinder Assy.	X	X	X	
53G41420-4	MLG Outer Cylinder	X	X	X	
32-41672-3	Main Torque Pins (Lower)	X	X	X	
32-41672-4	Main Torque Pins (Lower)	X	X	X	
32-41672-5	Main Torque Pins (Lower)	X	X	X	
32-41672-6	Main Torque Pins (Lower)	X	X	X	
32-45703-1	Nose Outer Cylinder Assy.	X	X	X	
32-41669-13	MLG Torque Arm Lower	X	X		
53-41441-3	MLG Axle Nut	X	X	X	
	F-16				
2006803-105	NLG Upper Drag Brace	X	X		
2006101-103	MLG Piston Assy.	X	X	X	
	A7D				
986118-1	Main Outer Cylinder	X	X	X	
	F-5				
14-40646-3	Main Torque Arm	X	X	X	
	F-15				
—	Main Outer Cylinder	X	X	X	
68A410615-2001	Main Collar Nut	X	X	X	
68A450726-2001	NLG Orifice Tube	X	X	X	
68A410792-1001	Main Lower Drag Brace	X	X	X	
68A410790-2001	MLG High Pressure Piston	X	X		
MS14163-09024	Bolts	X	X		
68A410756-1001	Main Jury Link Pin	X			ID
68A410735-2001	Main Trunnion Pin	X			ID
68A410755-2005	Main Jury Brace Appx. Pin	X			ID
68A450614-2001	NLG Miscellaneous	X			ID

Key:
ID – Insufficient IVD aluminum coverage on the inside diameter of the part
T-T – Torque-Tension

TABLE 41. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE OGDEN ALC (CONTINUED).

Part Number	Part Name	IVD Substitution for Cadmium			
		Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
	F-111				
121095-7	MLG Aft Hinge Pin	X	X		
993102-1	Main Inner Position	X	X	X	
1130121-101	Main Inner Cylinder	X	X	X	
	B52				
5-85123-6	Main Inner Cylinder	X			ID
4-80536	Drag Brace Pin, Toggle Fork	X			ID
25-4211	Main Lower Tripod Assy.	X	X		
1-80614	Drag Strut – Upper Link	X	X	X	
1-80615	Drag Strut – Upper Link	X	X	X	
5-68457-5	Steering Plate	X	X	X	
3-80616	Drag Strut	X	X	X	
1-80721-1	Main Torque Arm	X	X	X	
5-36035-3	Main Outboard Tripod Link	X		X	ID
6-35161-1	MLG Bolt	X			ID
6-35161-4	MLG Bolt	X			ID
4-80728	MLG Nut, Special	X	X	X	
6-34595-1	MLG Bolt	X			ID
63-214	Miscellaneous Parts	X	X		
4-80720	MLG Pin Special	X	X		
9-52976	Main Cap Trunnion	X	X	X	
9-52977	Main Cap Trunnion	X	X	X	
	A10				
19064-1	Main Pin Socket Sub Assy.	X			ID
	F-100				
NAS14882	Tie Bolt – Large Allen Head	X	X		
63B32436	Nut	X	X		
	C141				
9525611	Washer	X	X		
3G10018-113	Main Piston Assy	X			ID
3G11098-105	Main Axle	X			ID
3G61097-107	Nose Aft Drag Brace	X	X		
3G61344	Mooring Ring	X	X	X	
3G61303-101	Nut	X	X	X	
3G61342-101	Bolt (M.R.)	X	X	X	
3G61345	Spring (M.R.)	X	X	X	
3G11098-105	Main Axle	X			ID
3G111125-103	Main Knee Bolt	X			ID

Key:
ID – Insufficient IVD aluminum coverage on the inside diameter of the part
T-T – Torque-Tension

TABLE 41. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE OGDEN ALC (CONTINUED).

Part Number	Part Name	IVD Substitution for Cadmium			
		Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
	C141 (Continued)				
3G10008-105	Main Lower Torque Arm	X	X		
3G10017-133	Main Outer Cylinder	X	X	X	
3G11117-103	Main Drag Latch	X	X	X	
3F31004-123	Upper Drag Brace	X	X	X	
3G61089-111	Nose Inner Cylinder	X			ID
3G11077-103	Main Brake Link Torque Pin	X			ID
3G11112-107	Main Pivot Pin	X			ID
3G61032-107	Nose Axle	X			ID
3G61126-103	Nose Downlock Crank	X	X	X	
3G61090-119	Nose Outer Cylinder	X	X	X	
MS2125D-08024	Miscellaneous Bolts	X	X		
9525609	Miscellaneous Washers	X	X		
3G61014-101	Nose Trunnion Pin	X			ID
3G11825-101	Main Retract Fitting	X	X	X	
3G11081-101	MLG Nut (Bearing Retainer)	X	X		
3G11101-101	Bogie Beam Jacking Adapter	X	X	X	
3G11106-101	Bogie Beam Bolt Assy.	X	X	X	
3G11170-101	Bogie Beam Bolt	X	X	X	
3GF11165-101	Bogie Beam Lock Tab	X	X	X	
3G11102-101	Bogie Beam Bearing Plate	X	X	X	
CYW1018	Miscellaneous Nut	X	X		
3F31001-113	Main Lower Drag Brace	X	X		
3F31001-114	Main Lower Drag Brace	X	X		
7127998-001	Nose Gland Nut	X	X		
3G10013-111	Main Forward	X	X		
3G11826-101	Spacer	X	X	X	
	C/KC 135				
50-9717-25	Oleo Trunnion	X			ID
7531263-10	Nose Piston	X			ID
5-840011-27	Main Side Strut Upper	X	X	X	
7531263-10	Nose Piston	X			ID
69-1172-1	Brace Collar	X	X		
93-8670	Main Trunnion	X	X	X	
89-1172-1	MLG Brake Collar	X	X		
65-1336-3	Nose Upper Link	X	X	X	
65-1382-15-2	Nose Plate Gear Drag Plate	X	X	X	
65-1382-15-6	Nose Plate Gear Drag Plate	X	X	X	
65-4827	Nose Lower Link	X	X	X	

Key:
ID – Insufficient IVD aluminum coverage on the inside diameter of the part
T-T – Torque-Tension

TABLE 41. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE OGDEN ALC (CONCLUDED).

Part Number	Part Name	IVD Substitution for Cadmium			
		Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
	C/KC 135 (Continued)				
7729421-01	Nose Trunnion Pin	X			ID
5-840011-28	Main Side Strut	X	X	X	
90-8670	Main Trunnion Collar	X	X	X	
50-9717-3	Main Oleo Trunnion	X			ID
50-9717-4	Main Oleo Trunnion	X			ID
1583-85	MLG Beam Assy.	X			ID
50-9733-1	Main Drag Strut	X	X	X	
30-3115-3	MLG Gland Nut Lock	X	X	X	
9-55622-3	Nose Arm Assy.	X	X	X	
6-68013-2000	Drag Brace Arm	X	X	X	
MS20002-C8	Washer	X	X		
146936	Bleeder Adapter	X	X		
	T38				
3-41605-1	Nose Piston	X			ID
9756C49	NLG Pad, Lock	X	X	X	
	LAV88 A/A				
3088476-1-1	Miscellaneous Parts	X	X		
3088476-1-2	Miscellaneous Parts	X	X		

Key:
ID – Insufficient IVD aluminum coverage on the inside diameter of the part
T-T – *Torque-Tension*

TABLE 42. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE SACRAMENTO ALC.

Part Number	Part Name	IVD Substitution for Cadmium			
		Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
	C135				
5-86077	Terminal	X	X		
5-86079	Cap	X	X		
581C5	Barrel	X			ID
5-86397-2	Rod End	X	X		
5-86077	Terminal	X	X		
9-10386	Nut	X	X		
NAS1305-9H	Miscellaneous Hardware	X	X		
9-60396	Nut	X	X		
69-5156	Rod End	X	X		
66-13798-1	Ext. Sleeve	X	X		
65-6516-2	Head End	X	X		
65-12228-1	Bearing	X	X		
	F-111				
—	Miscellaneous Fasteners	X	X		
12W415-1	Wing Pivot Pin	X			ID
12T9201	Hub Assy				
	Hub	X			ID
	O B Bearing	X	X		
	Intercoastal – 9	X	X		
	Intercoastal – 7	X	X		
	PP-6583 T				
373511-1	Power Supply Cabinet	X	X		
	E-3A				
506826	Cylinder	X	X		
	B52				
5-36060-2	Piston Rod	X	X		
5-35988-1	Barrel	X			ID
65-043115	Side Plate	X	X		
65-043116	Side Plate	X	X		
	C5				
177269	Carrier Output	X	X		
177910	1FR Large	X	X		
177219	Carrier Output	X	X		
177515	Retainer Ring	X	X		
177386	Bevel Adaptor	X	X		
177246	Center Spur Gear				
	1 2 Details	X	X		
	1 2 Details	X			ID
1^7316	Adapter Spline	X			ID

Key
ID - Insufficient IVD aluminum coverage on the inside diameter of the part

TABLE 42. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE SACRAMENTO ALC (CONCLUDED).

Part Number	Part Name	IVD Substitution for Cadmium			
		Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
	F-15				
3831339-5	Piston	X			ID
3151-014	Nut	X	X		
	F-16				
2006020-1	Piston	X			ID
	F-4				
2219109	Gland Nut	X	X		
	C130				
19106	Forks	X	X		
457016-1	Ball Screws	X			ID
	C141				
186254	Piston	X			ID
188529	Piston	X			ID
	Miscellaneous Parts				
MPN 14	Barrel Pin	X	X		
MPN 14	Steel Plates	X	X		
TRN-19	Bracket (4 Details)	X	X		
636	Nuts	X	X		
A700-4600002-4700	Regulator Box (Several Pieces)	X	X		
77C10003	E-XMTR BTM Plate	X	X		
77010806-1	E-RX BTMPL-Assy.	X	X		
3831000-16	GTL-PTS	X	X		
58580-1	Blades	X	X		
301357	Solonoid Bracket	X	X		
202641	Standoff Bracket	X	X		
C387	Fastener	X	X		
MAG2566Z	Liner	X	X		
6-62681	Nut	X	X		
1P1064	CRT Shield LM	X			ID
9-45511-2	Sleeve	X	X		
MS21250-09022	Fuselage C.W. Attach Bolts	X	X		
MPS-9	Chassis	X	X		

Key
ID - Insufficient IVD aluminum coverage on the inside diameter of the part

TABLE 43. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE OKLAHOMA CITY ALC.

Engine Number	Part Number	Part Name	IVD Substitution for Cadmium			
			Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
		TF30				
30386R	697634	Shaft – Front Compressor Drive Turbine	X			ID
30334R	563559	Shaft – Front Compressor Drive Turbine	X			ID
30334R	617855	Shaft – Front Compressor Drive Turbine	X			ID
30469R	615770	Compressor Stator, 10th Stage	X	X		
30469R	564270	Compressor Stator, 10 – 14th Stage	X	X		
30469R	581980	Compressor Stator, 10 – 14th Stage	X	X		
30469R	615771	Compressor Stator, 10 – 14th Stage	X	X		
30469R	558481	Compressor Stator, 10 – 14th Stage	X	X		
30469R	615772	Compressor Stator, 10 – 14th Stage	X	X		
30469R	558482	Compressor Stator, 10 – 14th Stage	X	X		
30469R	581982	Compressor Stator, 10 – 14th Stage	X	X		
30469R	623873	Compressor Stator, 10 – 14th Stage	X	X		
30469R	577373	Compressor Stator, 10 – 14th Stage	X	X		
30469R	577374	Compressor Stator, 10 – 14th Stage	X	X		
30469R	623874	Compressor Stator, 10 – 14th Stage	X	X		
30469R	581980	Compressor Stator, 10 – 14th Stage	X	X		
30489R	672994	Compressor Stator, 4th Stage	X	X		
30489R	735874	Compressor Stator, 4th Stage	X	X		
30489R	768784	Compressor Stator, 4th Stage	X	X		
30470R	672995	Compressor Stator, 5 – 8th Stage	X	X		
30470R	710296	Compressor Stator, 5 – 8th Stage	X	X		
30470R	672997	Compressor Stator, 5 – 8th Stage	X	X		
30470R	710298	Compressor Stator, 5 – 8th Stage	X	X		
30470R	735875	Compressor Stator, 5 – 8th Stage	X	X		
30470R	735876	Compressor Stator, 5 – 8th Stage	X	X		
30470R	735877	Compressor Stator, 5 – 8th Stage	X	X		
30470R	735878	Compressor Stator, 5 – 8th Stage	X	X		
30470R	735785	Compressor Stator, 5 – 8th Stage	X	X		
30470R	735786	Compressor Stator, 5 – 8th Stage	X	X		
30470R	735787	Compressor Stator, 5 – 8th Stage	X	X		
30470R	735788	Compressor Stator, 5 – 8th Stage	X	X		
30467R	668395	Compressor Stator, 5 – 7th Stage	X	X		
30467R	675776	Compressor Stator, 5 – 7th Stage	X	X		
30467R	668396	Compressor Stator, 5 – 7th Stage	X	X		
30467R	675777	Compressor Stator, 5 – 7th Stage	X	X		
30467R	668397	Compressor Stator, 5 – 7th Stage	X	X		
30467R	2173319	Compressor Stator, 5 – 7th Stage	X	X		
30467R	NBN 049219	Compressor Stator, 5 – 7th Stage	X	X		

Key
ID – Insufficient IVD aluminum coverage on the inside diameter of the part

TABLE 43. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE OKLAHOMA CITY ALC (CONTINUED).

Engine Number	Part Number	Part Name	IVD Substitution for Cadmium			
			Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
		TF30 (Continued)				
30467R	2173318	Compressor Stator, 5 – 7th Stage	X	X		
30467R	NBN 049229	Compressor Stator, 5 – 7th Stage	X	X		
30467R	2173353	Compressor Stator, 5 – 7th Stage	X	X		
30467R	NBN 049378	Compressor Stator, 5 – 7th Stage	X	X		
30467R	2173354	Compressor Stator, 5 – 7th Stage	X	X		
30467R	NBN 049379	Compressor Stator, 5 – 7th Stage	X	X		
30467R	538085	Compressor Stator, 5 – 7th Stage	X	X		
30467R	618286	Compressor Stator, 5 – 7th Stage	X	X		
30467R	616997	Compressor Stator, 5 – 7th Stage	X	X		
30468R	668668	Compressor Stator, 8th Stage	X	X		
30468R	2173320	Compressor Stator, 8th Stage	X	X		
30468R	NBN 049230	Compressor Stator, 8th Stage	X	X		
30468R	557678	Compressor Stator, 8th Stage	X	X		
30450R	577338	Ring, Air Sealing, Compressor	X	X		
30450R	577339	Ring, Air Sealing, Compressor	X	X		
30450R	577340	Ring, Air Sealing, Compressor	X	X		
30450R	577341	Ring, Air Sealing, Compressor	X	X		
30450R	577342	Ring, Air Sealing, Compressor	X	X		
30450R	577343	Ring, Air Sealing, Compressor	X	X		
30450R	623760	Ring, Air Sealing, Compressor	X	X		
30450R	623761	Ring, Air Sealing, Compressor	X	X		
30450R	623762	Ring, Air Sealing, Compressor	X	X		
30450R	572613	Ring, Air Sealing, Compressor	X	X		
30450R	572614	Ring, Air Sealing, Compressor	X	X		
30584	559380	Tierod Bolts, Front Compressor	X	X	X	
30584	615992	Tierod Bolts, Front Compressor	X	X	X	
30568R	697032	Tierod Bolts, Rear and Front Compressor	X	X	X	
30737G	502178	Housing – Bearing Inter Gearbox	X	X	X	
30732G	618865	Housing Assembly Gearbox Bearing	X	X	X	
30732G	502366	Housing Assembly Gearbox Bearing	X	X	X	
30732G	502098	Housing Assembly Gearbox Bearing	X	X	X	
30732G	502184	Housing Assembly Gearbox Bearing	X	X	X	
30320R	559824	Coupling, Gearbox Drive Gear	X	X	X	
30318R	565084	Tube-Sealing Rear Compressor	X	X	X	
30594R	500756	Bracket, Ignition Exciter, Upper	X	X	X	
307556	666882	Housing Assembly Gearbox Bearing	X	X		
30334R	617855	Shaft N-1 Turbine	X			ID
30334R	563559	Shaft N-1 Turbine	X			ID
30670R	510790	Bracket	X	X		

Key
ID – Insufficient IVD aluminum coverage on the inside diameter of the part

TABLE 43. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE OKLAHOMA CITY ALC (CONTINUED).

Engine Number	Part Number	Part Name	IVD Substitution for Cadmium			
			Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
		TF30 (Continued)				
307156	739635	Housing Gearbox Drive Bearing	X	X	X	
30531R	559378	Tierod Bolts, Front Compressor	X	X	X	
30702G	702805	Nut Gearbox Quick Disconnect	X	X	X	
30702G	513799	Nut Gearbox Quick Disconnect	X	X	X	
30702G	504245 Sub	Nut Gearbox Quick Disconnect	X	X	X	
30702G	697220 Sub	Nut Gearbox Quick Disconnect	X	X	X	
30702G	504241	Nut Gearbox Quick Disconnect	X	X	X	
30702G	513798	Nut Gearbox Quick Disconnect	X	X	X	
30642G	697218	Adapter – Gearbox Quick Disconnect	X	X	X	
30642G	504255	Adapter – Gearbox Quick Disconnect	X	X	X	
30642G	697219	Adapter – Gearbox Quick Disconnect	X	X	X	
		TF33				
33342R	703556	Tierod, Front Compressor	X	X	X	
33342R	714147	Tierod, Front Compressor	X	X	X	
33342R	393540	Tierod, Front Compressor	X	X	X	
33342R	399032	Tierod, Front Compressor	X	X	X	
33342R	428335	Tierod, Front Compressor	X	X	X	
33342R	463547	Tierod, Front Compressor	X	X	X	
33342R	463553	Tierod, Front Compressor	X	X	X	
33342R	463554	Tierod, Front Compressor	X	X	X	
33342R	714149	Tierod, Front Compressor	X	X	X	
33342R	494399	Tierod, Front Compressor	X	X	X	
33342R	431122	Tierod, Front Compressor	X	X	X	
33342R	463557	Tierod, Front Compressor	X	X	X	
33342R	714145	Tierod, Front Compressor	X	X	X	
33342R	714162	Tierod, Front Compressor	X	X	X	
33342R	629236	Tierod, Front Compressor	X	X	X	
33342R	703558	Tierod, Front Compressor	X	X	X	
33342R	635508	Tierod, Front Compressor	X	X	X	
33346R	247346	Coupling, Front Compressor Drive Turbine	X			ID
33346R	432595	Coupling, Front Compressor Drive Turbine	X			ID
33346R	576584	Coupling, Front Compressor Drive Turbine	X			ID
33218R	483277	Housing No. 1 Bearing	X	X		
33218R	679747	Housing No. 1 Bearing	X	X		
33213R	769553	Housing No. 1 Bearing	X	X		
33354R	157532	Ring-Retaining L S Compressor Coupling	X	X	X	

Key
ID – Insufficient IVD aluminum coverage on the inside diameter of the part

TABLE 43. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE OKLAHOMA CITY ALC (CONTINUED).

Engine Number	Part Number	Part Name	IVD Substitution for Cadmium			
			Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
		TF33 (Continued)				
33352R	286079	Lock, Front Compressor Drive Turbine	X	X	X	
33352R	201615	Lock, Front Compressor Drive Turbine	X	X	X	
33352R	714163	Lock, Front Compressor Drive Turbine	X	X	X	
33897	403326	Accessory Drive Pad	X	X		
—	799599	Retainer	X	X		
33348R	359439	Seat, Turbine, Shaft Coupling	X	X		
33348R	364827	Seat, Turbine, Shaft Coupling	X	X		
33348R	714165	Seat, Turbine, Shaft Coupling	X	X		
33348R	208178	Spring, Front Compressor Turbine Shaft	X	X	X	
33897	403326	Nut Assembly, Accessory Drive Pad	X	X		
33670	464162	Sort Items (Bracket, Plate, Etc.)	X	X		
—	515970	Support	X			ID
		TF57				
57322R	740005	Spacer, High Speed Compressor	X	X		
57322R	206931	Spacer, High Speed Compressor	X	X		
57322R	740013	Spacer, High Speed Compressor	X	X		
57322R	310978	Spacer, High Speed Compressor	X	X		
57322R	740012	Spacer, High Speed Compressor	X	X		
57322R	216915	Spacer, High Speed Compressor	X	X		
57322R	740011	Spacer, High Speed Compressor	X	X		
57322R	216913	Spacer, High Speed Compressor	X	X		
57322R	740006	Spacer, High Speed Compressor	X	X		
57322R	206935	Spacer, High Speed Compressor	X	X		
57322R	740007	Spacer, High Speed Compressor	X	X		
57322R	206935	Spacer, High Speed Compressor	X	X		
57322R	740008	Spacer, High Speed Compressor	X	X		
57322R	206936	Spacer, High Speed Compressor	X	X		
57306R	183154	Tierod, Front and Rear Compressor	X	X	X	
57306R	201613	Tierod, Front and Rear Compressor	X	X	X	
57306R	369479	Tierod, Front and Rear Compressor	X	X	X	
57373R	201615	Coupling, Front Compressor Drive Turbine Shaft	X			ID
57373R	714163	Coupling, Front Compressor Drive Turbine Shaft	X			ID
57373R	286079	Coupling, Front Compressor Drive Turbine Shaft	X			ID
57370R	201616	Collar, Front Compressor Drive Turbine Shaft Coupling	X	X		
57370R	331450	Collar, Front Compressor Drive Turbine Shaft Coupling	X	X		

Key
ID - Insufficient IVD aluminum coverage on the inside diameter of the part

TABLE 43. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE OKLAHOMA CITY ALC (CONCLUDED).

Engine Number	Part Number	Part Name	IVD Substitution for Cadmium			
			Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
		TF57 (Continued)				
57373M	714163	Lock, Front Compressor Drive Turbine Shaft Coupling	X	X		
57373M	201612	Lock, Front Compressor Drive Turbine Shaft Coupling	X	X		
57743R	334974	Screen Assembly, Water Injector Control Inlet	X	X		
57670Y	334974	Screen Assembly, Water Injector Control Inlet	X	X		
57743R	321530	Screen Assembly, Water Injector Control Inlet	X	X		
57723Y	403326	Nut Assembly, Accessory Drive Pad	X	X		
57723M	403326	Nut Assembly, Accessory Drive Pad	X	X		
57723M	308892	Nut Assembly, Accessory Drive Pad	X	X		
57369Y	157532	Ring-Retaining L S Compressor Coupling	X	X	X	
57372Y	208178	Spring, Front Compressor Turbine Shaft	X	X	X	
57327R	208178	Spring, Front Compressor Turbine Shaft	X	X	X	
575078	739635B	AB Cylinder	X	X		
		Miscellaneous Parts				
—	—	Seat, Turbine Shaft, Coupling Lock Spring	X	X		
—	—	P&W Ring, 6th Stage	X	X		
41763R	6865326	Link Bell Crank Rod Assembly	X	X		
41900R	6861241	Rear Mounting – Regular Airflow Control	X	X		
A00094	204104	Carrier	X	X		

Key:
ID – Insufficient IVD aluminum coverage on the inside diameter of the part

TABLE 44. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE SAN ANTONIO ALC.

Part Number	Part Name	IVD Substitution for Cadmium			
		Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
	T56				
6829896	Pin Reduction Gear Eye Bolt	X	X		
6841212	Compressor Wheel, Stage 2	X	X	X	
6841213	Compressor Wheel, Stage 3	X	X	X	
6841214	Compressor Wheel, Stage 4	X	X	X	
6841215	Compressor Wheel, Stage 5	X	X	X	
6847091	Vane Compressor, 1st Stage	X	X		
6875201	Vane Compressor, 1st Stage	X	X		
6876251	Vane Compressor, 1st Stage	X	X		
6847093	Vane Compressor, 3rd Stage	X	X		
6875203	Vane Compressor, 3rd Stage	X	X		
6875206	Vane Compressor, 6th Stage	X	X		
6809436	Vane Compressor, 6th Stage	X	X		
6875210	Vane Compressor, 10th Stage	X	X		
6875211	Vane Compressor, 11th Stage	X	X		
6809441	Vane Compressor, 11th Stage	X	X		
6846291	Vane Compressor, 11th Stage	X	X		
6855041	Vane Compressor, 11th Stage	X	X		
6859611	Vane Compressor, 11th Stage	X	X		
6871381	Vane Compressor, 11th Stage	X	X		
6809432	Vane Compressor, 2nd Stage	X	X		
6846872	Vane Compressor, 2nd Stage	X	X		
6855032	Vane Compressor, 2nd Stage	X	X		
6859602	Vane Compressor, 2nd Stage	X	X		
6846672	Vane Compressor, 2nd Stage	X	X		
6846282	Vane Compressor, 2nd Stage	X	X		
6871372	Vane Compressor, 2nd Stage	X	X		
6847091	Vane Compressor, 1st Stage	X	X		
6875201	Vane Compressor, 1st Stage	X	X		
6876251	Vane Compressor, 1st Stage	X	X		
6859604	Vane Compressor, 4th Stage	X	X		
6809434	Vane Compressor, 4th Stage	X	X		
6846871	Vane Compressor, 4th Stage	X	X		
6855034	Vane Compressor, 4th Stage	X	X		
6846674	Vane Compressor, 4th Stage	X	X		
6846284	Vane Compressor, 4th Stage	X	X		
6871374	Vane Compressor, 4th Stage	X	X		
6809435	Vane Compressor, 5th Stage	X	X		
6846875	Vane Compressor, 5th Stage	X	X		

Key
ID – Insufficient IVD aluminum coverage on the inside diameter of the part
T-T – Torque-Tension

TABLE 44. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE SAN ANTONIO ALC (CONTINUED).

Part Number	Part Name	IVD Substitution for Cadmium			
		Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
	T56 (Continued)				
6875204	Vane Compressor, 4th Stage	X	X		
6847094	Vane Compressor, 4th Stage	X	X		
6847095	Vane Compressor, 5th Stage	X	X		
6875205	Vane Compressor, 5th Stage	X	X		
6847077	Vane Compressor, 7th Stage	X	X		
6875207	Vane Compressor, 7th Stage	X	X		
6875208	Vane Compressor, 8th Stage	X	X		
6875209	Vane Compressor, 9th Stage	X	X		
6875212	Vane Compressor, 12th Stage	X	X		
6875213	Vane Compressor, 13th Stage	X	X		
6814423	Rear Lever Propeller Control	X	X		
6812539	Shaft Propeller Control Lever, Intermediate	X	X		
6819691	Shaft Propeller Control Lever, Intermediate	X	X		
6819697	Shaft Propeller Control Lever, Intermediate	X	X		
6819694	Bolt Propeller Control Pivot	X			T-T
6819698	Clevis	X	X		
6821487	Arm Propeller Control, Intermediate	X	X		
6824774	Bolt Reduction Gear	X	X		
6826933	Arm Propeller Control, Front	X	X		
6826934	Bell Crank PC1	X	X		
6826935	Arm Propeller Control, Rear	X	X	X	
6827298	Link Propeller Control, Rear	X			ID
6780854	Rod, Threaded Level FUF1	X	X		
6781501	Rod, Threaded Level FUF1	X	X		
6783838	Fitting Reduction Gear Power	X	X		
6854756	Compressor Wheel, Stage 6	X	X	X	
6855286	Compressor Wheel, Stage 6	X	X	X	
6858624	Compressor Wheel, Stage 14	X	X	X	
6824074	Compressor Wheel, Stage 14	X	X	X	
6875958	Propeller Shaft	X			ID
6789474	Vane Compressor, 14th Stage	X	X		
6731014	Vane Compressor, 14th Stage	X	X		
6791891	Engine Mount Bracket Assembly	X	X	X	
6792254	Seal, Labyrinth Rotating Compressor	X	X	X	
6792767	Compressor Wheel, Stage 14	X	X	X	
6792768	Compressor Wheel, Stage 8	X	X	X	
6792770	Compressor Wheel, Stage 9	X	X	X	
6792771	Compressor Wheel, Stage 11	X	X	X	

Key
ID -- Insufficient IVD aluminum coverage on the inside diameter of the part
T-T -- Torque-Tension

TABLE 44. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE SAN ANTONIO ALC (CONTINUED).

Part Number	Part Name	IVD Substitution for Cadmium			
		Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
	T56 (Continued)				
6855035	Vane Compressor, 5th Stage	X	X		
6859605	Vane Compressor, 5th Stage	X	X		
6846675	Vane Compressor, 5th Stage	X	X		
6846285	Vane Compressor, 5th Stage	X	X		
6871375	Vane Compressor, 5th Stage	X	X		
6809437	Vane Compressor, 7th Stage	X	X		
6855037	Vane Compressor, 7th Stage	X	X		
6859607	Vane Compressor, 7th Stage	X	X		
6846287	Vane Compressor, 7th Stage	X	X		
6871377	Vane Compressor, 7th Stage	X	X		
6809438	Vane Compressor, 8th Stage	X	X		
6855038	Vane Compressor, 8th Stage	X	X		
6859608	Vane Compressor, 8th Stage	X	X		
6846288	Vane Compressor, 8th Stage	X	X		
6871378	Vane Compressor, 8th Stage	X	X		
6809439	Vane Compressor, 9th Stage	X	X		
6855039	Vane Compressor, 9th Stage	X	X		
6859609	Vane Compressor, 9th Stage	X	X		
6871379	Vane Compressor, 9th Stage	X	X		
6809440	Vane Compressor, 10th Stage	X	X		
6855040	Vane Compressor, 10th Stage	X	X		
6859610	Vane Compressor, 10th Stage	X	X		
6846290	Vane Compressor, 10th Stage	X	X		
6871380	Vane Compressor, 10th Stage	X	X		
6809442	Vane Compressor, 12th Stage	X	X		
6855042	Vane Compressor, 12th Stage	X	X		
6859612	Vane Compressor, 12th Stage	X	X		
6846292	Vane Compressor, 12th Stage	X	X		
6871382	Vane Compressor, 12th Stage	X	X		
6809443	Vane Compressor, 13th Stage	X	X		
6855043	Vane Compressor, 13th Stage	X	X		
6859613	Vane Compressor, 13th Stage	X	X		
6846293	Vane Compressor, 13th Stage	X	X		
6871383	Vane Compressor, 13th Stage	X	X		
6846871	Vane Compressor, 1st Stage	X	X		
6855031	Vane Compressor, 1st Stage	X	X		
6859601	Vane Compressor, 1st Stage	X	X		
6875202	Vane Compressor, 2nd Stage	X	X		

Key
ID – Insufficient IVD aluminum coverage on the inside diameter of the part
T-T – Torque-Tension

TABLE 44. REVIEW OF PARTS FOR THE SUBSTITUTION OF IVD ALUMINUM FOR CADMIUM AT THE SAN ANTONIO ALC (CONCLUDED).

Part Number	Part Name	IVD Substitution for Cadmium			
		Part Reviewed	Problem Free	IVD Use Approved	Area of Concern
	T56 (Continued)				
6792772	Compressor Wheel, Stage 12	X	X	X	
6794722	Seal, Labyrinth Compressor, Rear	X	X	X	
	F100				
4001860	Nut Bearing Retaining	X	X		
4010237	Nut Bearing Retaining	X	X		
4022555	Coupling Remote	X			ID

Key:
ID – Insufficient IVD aluminum coverage on the inside diameter of the part
T-T – Torque- Tension

the total number of parts reviewed. The percentage of parts exhibiting "areas of concern" is somewhat less than what was initially suspected, nominally 20 percent. The total number of parts identified with possible torque-tension or erosion problems may be low. But, the percentage of parts with "areas of concern" is not expected to exceed 15-18 percent.

Although all of the parts processed by the ALCs are not available for review at any given time, the majority of the part configurations were reviewed at each ALC. From this review, the majority of cadmium processed parts could now be IVD aluminum coated. Even thought the percentage of parts with "areas of concern" is relatively low, adequate solutions for the problem parts must be establish before IVD aluminum can replace cadmium processing across-the-board at the ALCs. Research and development directed at resolving these "areas of concern" is discussed in Section XII. A high probability of success is projected.

C. DEMONSTRATION OF THE GENERIC NATURE OF IVD ALUMINUM

MCAIR demonstrated the generic properties of IVD aluminum (Reference 92) as discussed in Sections II through VII by testing IVD aluminum-coated panel. Thirty-six 1- by 4-inch and 12, 3- by 6-inch panels were IVD aluminum coated per the test matrix in Table 45. Three substrate materials were used with three coating thickness classes for each substrate material.

The adhesion of the IVD aluminum coating was verified on the 36, 1- by 4-inch bend-to-break panels. Paragraph 4.5.2 of MIL-C-83488 defines adhesion. "Adhesion shall be determined by scraping the surface of the plated article to expose the basis metal and examining at a minimum of four diameters magnification for evidence of nonadhesion. Alternately, the test strip shall be clamped in a vise and bent back and forth until strip rupture occurs. If the edge of the ruptured coating can be peeled back or if separation between the coating and the basis metal can be seen at the point of rupture when examined at four diameters magnification, adhesion is not satisfactory." All 36 IVD aluminum-coated panels passed the bend-to-break test. In addition, all 36 panels were tape-tested and glass-bead-peened for adhesion verification, and six panels had the adhesive strength of the coating measured.

TABLE 45. TEST MATRIX FOR DEMONSTRATION OF THE GENERIC NATURE OF IVD ALUMINUM.

Test	Number of Coupons Required to Be Coated					
	Alloy Steel		Aluminum Alloy		Titanium Alloy	
	Specimen Size		Specimen Size		Specimen Size	
	3 × 6 (in.)	1 × 4 (in.)	3 × 6 (in.)	1 × 4 (in.)	3 × 6 (in.)	1 × 4 (in.)
1 Corrosion Resistance						
Class 1 Coating	4	—	—	—	—	—
Class 2 Coating	4	—	—	—	—	—
Class 3 Coating	4	—	—	—	—	—
2 Adhesion						
Class 1 Coating	—	4	—	4	—	4
Class 2 Coating	—	4	—	4	—	4
Class 3 Coating	—	4	—	4	—	4
3 Uniformity	—	4	—	4	—	4
4 Coverage	—	4	—	4	—	4
5 Conductivity	—	4	—	4	—	4

Notes:
1. Corrosion resistance testing will be conducted per ASTM B-117 (5 percent neutral salt fog environment)
2. Coating adhesion shall pass bend-to-brake testing and 40 psi glass bead peening.
3. Coating uniformity shall be measured on the 3- by 6-in. alloy steel panel prior to corrosion resistance testing.
4. Coating coverage shall be verified by 4× visual inspection on all of the 1- by 4-in. coupons prior to adhesion testing.
5. Electrical conductivity shall be measured on all the 1- by 4-in. coupons prior to adhesion testing.
6. Dash (—) indicates no test specimen.

The tape test was performed by firmly applying Number 250, 3M Company, inspection tape to the fractured edge of the bend-to-break panels and removing with a quick pull. No coating was removed from the fractured edge of the panels.

Prior to the bend-to-break and tape tests, the panels were glass-bead-peened at 40 psi with Number 10 glass beads. The impinging glass beads produce shear stresses in the coating sufficient to remove poorly adherent coatings. No coating was removed by glass bead peening.

A pull test was performed on six of the 1- by 4-inch steel panels, two from each coating thickness class. A Sebastian I Coating Adherence Tester with a 10 KPSI range was used for these tests. The adhesive tensile strength of the IVD aluminum coating was greater than 8 KPSI for all three classes of coatings.

In conclusion, the adhesion of the IVD aluminum coating on these panels is representative of IVD aluminum-coated parts that are properly processed. These adhesion tests demonstrate the generic nature of the coating adhesion reported in Section II(A).

Coating coverage was verified for each of the 1- by 4-inch panels by a visual inspection prior to adhesion testing. A Bausch & Lomb Stereo microscope, Model 31-270-01, was used to examine the coating for bare areas, blisters, and voids in the coating. The IVD aluminum completely covered the panels.

The coating uniformity was measured on the 12, 4130 alloy steel test panels. The IVD aluminum-coating thicknesses are presented in Table 46.

TABLE 46. IVD ALUMINUM COATING THICKNESS AND UNIFORMITY ON THE GENERIC PANELS.

Specimen Number	Coating Class	Coating Thickness (mils)[a, b]	
		Individual Measurements	Average
1	1	1.35, 1.39, 1.54, 1.59, 1.49	1.47
2		1.49, 1.49, 1.39, 1.39, 1.49	1.45
3		1.59, 1.65, 1.49, 1.39, 1.39	1.50
4		1.49, 1.44, 1.49, 1.54, 1.54	1.50
5	2	0.93, 0.93, 0.96, 0.99, 0.90	0.94
6		0.99, 0.99, 0.90, 0.85, 0.85	0.96
7		0.99, 0.99, 0.99, 0.90, 0.90	0.95
8		0.93, 0.83, 0.85, 0.93, 0.99	0.91
9	3	0.48, 0.49, 0.48, 0.48, 0.47	0.48
10		0.50, 0.47, 0.47, 0.47, 0.48	0.48
11		0.50, 0.48, 0.46, 0.47, 0.50	0.48
12		0.49, 0.50, 0.46, 0.47, 0.49	0.48

a Coating thickness measurements were obtained using the Magne-gage instrument

b Measurements were taken 1 in. in from each corner and in the center of the 3- by 6-in. panels

In conclusion, the coverage, uniformity, and thickness on these panels is representative of IVD aluminum-coated parts that are properly processed. The coverage and uniformity measurements demonstrate the generic nature of the process reported in Section II(B).

The electrical conductivity of the IVD aluminum coating was calculated from 4-point probe voltage, current, and probe characteristics. Four-point probe measurements were made using a Keithley model 181 nanovoltmeter, in conjunction with an Alessi 4 point probe head and fixture. A nonmetallic panel was coated with a Class 1 IVD aluminum coating, and its electrical conductivity was compared to a bulk specimen of 1100 aluminum alloy which has a 99 percent minimum aluminum content. The IVD aluminum coating has an electrical conductivity of 47.6 percent that of bulk aluminum transverse to the surface. This is significant in that bulk aluminum is approximately three times more conductive than cadmium.

In conclusion, IVD aluminum coating on these panels is electrically conductive and provides a low resistant path. The electrical conductivity measurements demonstrate the generic nature of the coating reported in Section II(E).

IVD aluminum corrosion resistance was tested on the 12, 3- by 6-inch alloy steel panels in neutral salt fog per ASTM B-117. All the specimens for each coating class exceeded the minimum requirements of MIL-C-83488. The average time to failure (red rust) for the Class 3 panels was 1,424 hours. The average time to failure for the Class 2 panels is more than 7,300 hours (one panel is still in test). The average time to failure for the Class 1 coating is more than 7,800 hours (all four panels are still in test). The MIL-C-83488 corrosion-resistance requirements, the average time to failure for the large database shown in Figure 12, Section III(A), and the average time to failure for the generic, aluminum-coated panels are shown in Figure 61. The average corrosion-resistance time of the generic, IVD aluminum-coated panels exceed the average times shown for the database in Figure 12.

In conclusion, IVD aluminum satisfied the minimum corrosion-resistance requirement of MIL-C-83488 and is representative of, to better than, the corrosion resistance expected for properly processed IVD aluminum-coated parts reported in Section III(A).

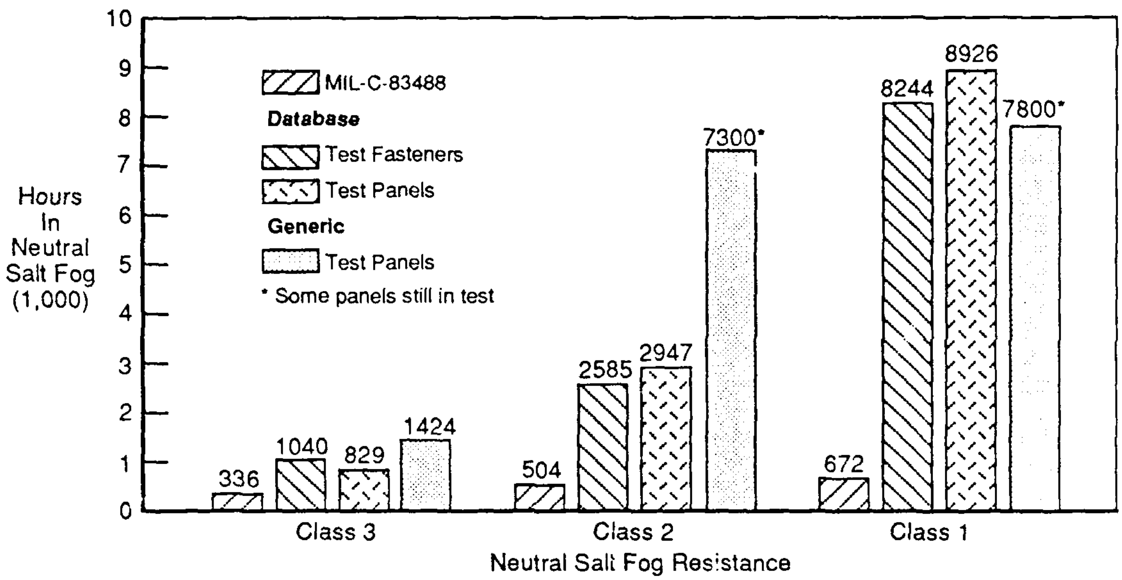


Figure 61. Average Test Results for the Generic Panels Versus Minimum Requirements of MIL-C-83488 and the Database Averages.

SECTION XI

CONCLUSIONS

IVD aluminum full-scale coating equipment is production proven; it was introduced for use in the manufacture of aircraft over 12 years ago. The coating has successfully undergone extensive laboratory and in-service testing as a substitute for cadmium -- many of the test results are documented herein. IVD aluminum is an excellent corrosion resistant finish and, in fact, offers performance advantages over cadmium. Perhaps more important, aluminum is nontoxic, and the IVD process is environmentally clean.

Because the IVD aluminum operation is clean, simple, and non-labor-intensive, and because facility and space requirements are minimal and require no special pollution-related systems, it is a cost-competitive process. Cadmium costs are increasing because of environmental and health related laws and regulations. At the same time, IVD aluminum costs are decreasing because of productivity advances associated with its increased usage.

The contents of this report verify that, for most applications, IVD aluminum can be substituted for cadmium without concern. For those applications where the substitution is not straightforward or where other technical issues must be considered, the reader is alerted and specific research programs are recommended. A high probability of success is projected. The contents of this report, therefore, strongly supports the elimination of the various hazardous-waste-producing cadmium processes.

SECTION XII

RESEARCH AND DEVELOPMENT RECOMMENDATIONS

A. COVERAGE OF INTERNAL SURFACES

1. Problem

Whereas the IVD aluminum process is not confined to line-of-sight application, it does have limitations regarding the ability to coat into deep recesses; see Section II(B). Generally speaking, the process can be used effectively to coat into a bore or recess for a distance equal to approximately one time the diameter of the opening. Therefore, for parts with a length-to-diameter ratio greater than 1:1 (or 2:1 if open at both ends), the IVD coating coverage on portions of the internal surface may be inadequate. For example, the bore of a 5-inch diameter cylinder 20-inches long and open at both ends would be coated effectively for approximately 5-inches from both ends. The remaining 10-inches of internal surface in the middle of the cylinder would have a thin coating or no coating at all.

Even though techniques may be available to evaporate aluminum within deep recesses using an internal anode, for most applications this procedure could be prohibitively expensive. Therefore, IVD aluminum cannot be a direct cadmium substitute for some ALC parts, such as landing gear details and turbine shafts, because of internal surface coating requirements. However, there are coatings that are compatible with IVD aluminum and are recommended alternatives to cadmium for internal surfaces.

2. Proposed Solution

Combined IVD aluminum with another coating to provide complete coverage of internal surfaces. Candidate materials include:

a. Aluminum-filled MIL-C-81517 basecoats.

b. Ceramic sealcoats.

c. Primers, topcoats, and sealants.

Aluminum-filled MIL-C-81517 basecoats - These are paint-type materials currently in use by the ALCs. The coatings can be brush- or spray-applied to internal surfaces. The aluminum-filled coating becomes electrically conductive when either cured at a sufficiently high temperature or burnished with glass beads. The electrically conductive coating then provides adequate sacrifical, corrosion-resistance protection to alloy steel substrates. Alseal®, Sermetel®, and Xylar® are tradenames of available aluminum filled coatings suitable for this application.

Ceramic sealcoats - The MIL-C-81517 aluminum-filled coatings are often used as a sacrificial metallic basecoat in combination with a ceramic sealcoat to improve corrosion resistance. DoD agencies such as the Naval Sea Systems Command make extensive use of these metallic-ceramic combination coatings to protect alloy steel hardware for various marine applications. The combination of IVD aluminum as the sacrificial aluminum basecoat enhanced with a ceramic sealcoat should provide adequate corrosion resistance to internal surfaces for those case where there is IVD aluminum coating coverage but thickness is less than desired.

Primer, topcoats, and sealants - Combinations of various primers, topcoats, and sealants have shown promise im preliminary testing and may afford acceptable corrosion-resistance protection to internal surfaces. Standard materials in use by the ALCs like epoxy primers, polyurethane topcoats, and sprayable sealants are candidates.

The question may be asked, "If a complementary coating is adequate for an internal surface, why not use that coating over the entire component rather than in combination with IVD aluminum, thus eliminating two-step processing?" The answer is that what may be adequate for internal surfaces my not be adequate for external surfaces. For example, the sacrificial aluminum-filled paint-type coatings provide excellent corrosion resistance and should be more than adequate to protect internal surfaces. However, internal surfaces are not normally subjected to the more harsh corrosive environments nor to the same harsh demands on coating adhesion as external surfaces. Therefore, the IVD aluminum process is recommended on all external surfaces and on as large a portion of the internal surfaces as possible. The reasons are that in addition to corrosion resistance, IVD aluminum provides superior coating adhesion and superior uniformity and coverage on part edges.

As an example, the external surfaces of landing gear details and turbine shafts are exposed to more harsh conditions than internal surfaces. The abrasive effects of take-offs and landings require a coating that adheres well and is resistant to chipping. The IVD aluminum coating does not chip; it is required that IVD coating adhesion pass the stringent bend-to-break coupon test. In contrast, the aluminum-filled paint type coatings are highly susceptible to the chipping type of nonadhesion. Typically, these coatings will not meet the bend-to-break adhesion requirement.

IVD aluminum also provides excellent coating uniformity and coverage on details in the transition area between external and internal surfaces. These areas often are threaded and/or contain sharp edges. IVD aluminum does not build up on or run off of sharp edges or thread crests/roots regardless of thickness. The paint and spray-type coatings will run off of edges and build up in recesses.

3. Recommended R&D Program

MCAIR proposes to identify and select candidate materials where required for internal surfaces to complement IVD aluminum. Processing procedures for combining these materials with IVD aluminum and applying them to internal surfaces will be developed. Testing for corrosion resistance will be performed. MCAIR will issue a report verifying that the candidate materials and developed procedures will:

a. Meet MIL-C-83488 corrosion resistance requirements.
b. Meet applicable adhesion requirements.
c. Comply with environmental standards.

B. IMPROVED EROSION RESISTANCE

1. Problem

IVD aluminum is relatively soft, as is cadmium. Neither is well suited for applications requiring a high degree of erosion resistance. Nickel-cadmium is more erosion resistant than cadmium by itself and is commonly used by the ALCs on engine details. IVD aluminum can easily be applied thicker than is normal for nickel-cadmium, and this advantage may result in comparable erosion resistance or even improved erosion/corrosion resistance. Thicker IVD aluminum coatings may not always be possible, however, because of tolerance limitations. Therefore, an improvement in erosion resistance is needed when using thinner IVD aluminum coatings.

2. Proposed Solution

Preliminary erosion resistance testing of an IVD aluminum basecoat enhanced by an erosion resistant topcoat has been encouraged. It is proposed that this work be continued. Work by Chromalloy Compressor Technologies, for example, demonstrated the erosion-resistant characteristics of an IVD aluminum basecoat with their specially formulate conversion topcoat (Reference 61). Although the comparison was not with a cadmium process, it does indicate the potential for such combination coatings.

Another area that may be investigated is the erosion resistance of various aluminum alloys applied in the IVD process. An aluminum alloy different than the soft, basically pure, 1100 aluminum alloy that is normally used may well provide improved erosion resistance, either by itself or in combination with a topcoat.

3. Recommended R&D Program

a. Identify candidate topcoats and aluminum alloys for improved erosion resistance.

b. Establish processing procedures.

c. Test for erosion resistance and the effect on corrosion resistance.

d. Verify environmental compliance.

A report will be issued comparing results with currently used processing, including nickel-cadmium.

C. IMPROVED LUBRICITY

1. Problem

Fasteners are often installed at particular torques that have been determined to give desired preloads. These torque values are usually required by the technical manuals supplied by the original equipment manufacturers (OEMs). Since aluminum is not as lubricious as cadmium, higher torque is required to install IVD aluminum-coated fasteners to a given preload than to install cadmium-plated fasteners. The OEMs are naturally reluctant to approve plating substitutions that do not provide similar torque/tension characteristics. The following excerpt exemplifies the problem. It is from the OEM report rejecting the use of IVD aluminum because of different torque/tension relationships. An ALC had asked for concurrence to change from electroplated cadmium and nickel-cadmium to IVD aluminum for turbine engine bolts.

> "A change in coatings changes the coefficient of friction thus affecting a torque required to achieve a given axial load. A significant change in torque requirements, as a result of Ivadize, would be unacceptable since production parts would continue to be coated with cadmium. It would be impractical and confusing to have two sets of torque values in assembly instructions and overhaul manuals. This author recommends that IVD aluminum not be used on the parts listed in Attachment 1."

2. Proposed Solution

The difference in torque/tension characteristics between aluminum and cadmium can be minimized by the use of lubricants; see Section V(A). The use of acceptable lubricants with the aluminum coating appears to be a better solution than changing technical manuals to reflect different torque requirements for different finishes. MCAIR proposes that with appropriate lubrication, IVD aluminum will meet any torque/tension requirement for any application.

IVD aluminum has already been demonstrated to be an acceptable substitution for cadmium on alloy steel fasteners. There is extensive laboratory and field service data supporting this position, much of it compiled in this report. MCAIR has long held that an IVD aluminum coating is, in fact, the best overall coating available for steel fasteners. Further, it has been demonstrated for MCAIR applications that the use of correct lubrication precludes the need to alter installation procedures and/or torque/tension values. The selection and use of proper lubricants should allow acceptable installation of IVD aluminum coated fasteners for any application, airframe or engine.

3. Recommended R&D Program

MCAIR proposes to identify various acceptable lubricants, depending upon the application. Detail parts will then be coated to required thicknesses, lubricated, and then tested for torque/tension characteristics. MCAIR proposes to issue a report compiling the above information which will show that the coating/lubricant combination:

a. Meets technical manual torque/tension requirements.
b. Complies with environmental standards.

MCAIR also proposes to coordinate the lubricant selectio. and data with appropriate OEMS.

D. IMPROVED CORROSION RESISTANCE

1. Problem

Although IVD aluminum is an excellent corrosion-resistant finish, improvements are always being sought to expand its usage and to solve chronic aircraft corrosion problems. Much research and development has been conducted toward this end. Except for the most recent several years, most of this research and development had been directed at increasing corrosion resistance by improving the IVD aluminum coating structure. A columnar structure is inherent with the IVD aluminum process. Efforts were directed primarily at making this columnar structure more amorphous and dense. Some of this research has shown promise. Increasing the ionization level of the aluminum vapor or increasing substrate temperature are examples. However, for the most part, production processing changes could not be justified on the basis of a cost benefit analysis.

More recent research has been directed at enhancing the corrosion resistance of the IVD aluminum basecoat by penetrating and sealing its columnar structure with a commercially available topcoat. Preliminary results have been promising. Therefore, it appears research in this area will provide the greatest gains in corrosion resistance, with the least adverse impact on cost or productivity.

2. Proposed Solution

Evaluate topcoats which will significantly improve corrosion resistance and can be justified on the basis of a cost benefit analysis. Preliminary research using Xylar® 101, commercially available ceramic topcoat, has shown considerable promise. Figure 62 is a photomicrogran of an alloy steel fastener processed with IVD aluminum plus Xylar® 101 after 9,000 hours in a 5 percent neutral salt fog environment. The fastener is still completely protected. The Xylar® 101 topcoat has penetrated and sealed the IVD aluminum coating.

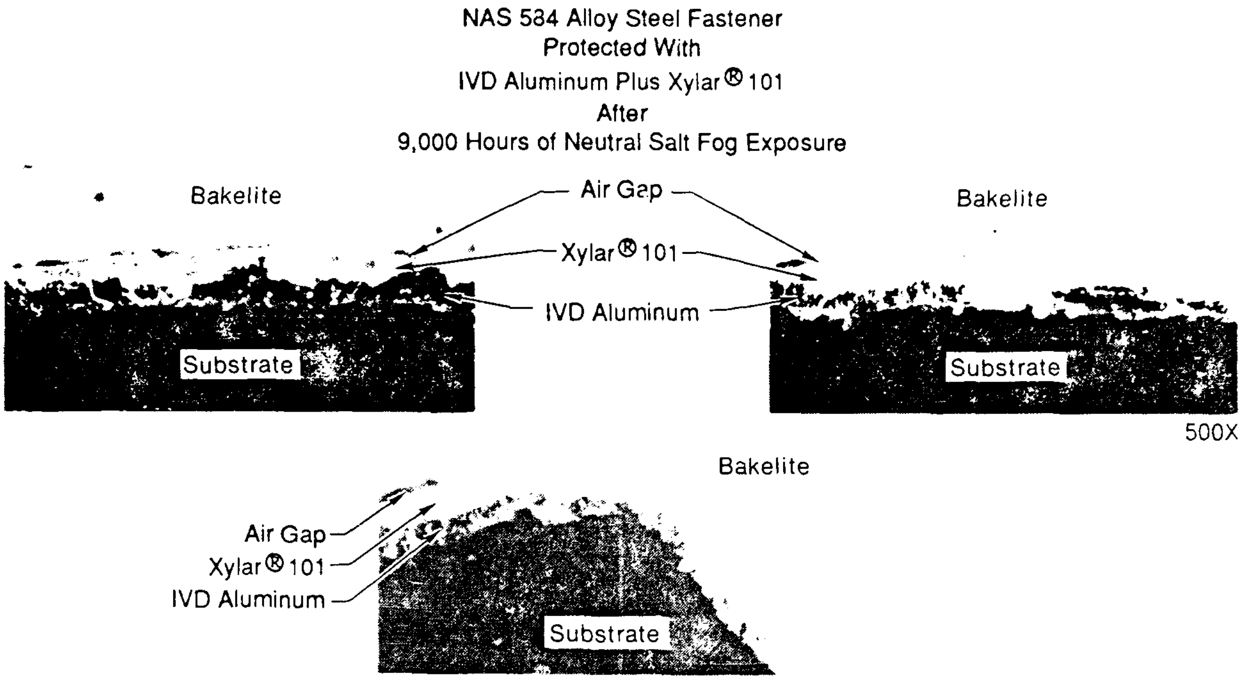


Figure 62. Magnified Cross-Section of IVD Aluminum and Xylar® 101.

In 1987, MCAIR conducted studies which confirmed that the use of a Xylar® 101 topcoat enhanced the corrosion resistance of IVD aluminum coated fasteners and hardware. In addition to improve corrosion resistance, the combination coating meets all of the requirements of the metallic-ceramic coating specification, MIL-C-81751, while providing the following advantages:

a. Superior coating coverage and uniformity - Current MIL-C-81751 basecoats are either sprayed or dip-applied. Both procedures result in coating run-off on edges and coating build-up in recesses. The IVD aluminum coating does not have these problems.

b. Superior coating adhesion - The current MIL-C-81751 adhesion requirement is less severe than the adhesion requirement for IVD aluminum. IVD aluminum will routinely pass the crushed fastener head adhesion test or the standard coupon bend-to-break test. Current MIL-C-81751 coatings will chip and flake. Poor adhesion is a persistent field problem for these coatings.

c. IVD/Xylar® is commercially available; this should lead to multiple, convenient sources of supply with competitive pricing.

3. Recommended R&D Program

MCAIR proposes to identify the most promising topcoat(s) by screening and testing additional candidates. Processing procedures will be established to produce the most cost effective finish system. Testing for corrosion resistance will be performed. MCAIR will issue a report verifying that the candidate topcoat(s) and developed procedures will:

a. Enhance the corrosion resistance of IVD aluminum.
b. Exceed MIL-C-83488 corrosion resistance requirements.
c. Meet applicable adhesion requirements.
d. Provide a base for acceptable paint adhesion.
e. Comply with environmental standards.

E. ZIRCONIUM COMPOUNDS AS A SUBSTITUTE FOR CHROMATE CONVERSION

1. Problem

Chromate conversion coatings significantly improve the corrosion resistance of both aluminum and cadmium protective finishes. Of equal importance is the fact that adhesion of paint coatings is also enhanced by the chromate complex on the aluminum surface. The conversion coating process involves immersing the parts in a tank of acidified chromate solution for a short period of time. As discussed in Section IX(C), chromate are an environmental problem. However, the chromate conversion treatment of both aluminum and cadmium finishes can be performed in an environmentally compliant manner. With good filtration systems, the amount of waste generated is minimal. Some of the current production tanks at MCAIR have operated 4-6 years without the need to change or dispose of solutions, which are handled as hazardous waste. As a result, there have been few economic pressures to find a more a pollution free process.

However, because there is a potential for chromium compounds to escape manufacturing facilities (through exhaust stacks or sewers, and contaminate the ground water, tough legislation such as California's Proposition 65 is now being enacted. This law limits exposure levels of many compounds, including chromium, and sets standards of disposal for some compounds lower than those allowed in public drinking water. Such laws will increase the costs of processing with a chromate conversion solution. Pollution control will have to be increased to prevent even minimal leakage into the environment. Both private industry and the ALCs should review all processes and make changes that result in the use of less toxic materials and generate little or no hazardous waste. This in turn will minimize the potential for adverse effects on the environment and improve cost efficiency.

2. Proposed Solution

Evaluate potential state-of-the-art replacements for chromates. Several companies are recommending zirconium compounds as replacements for chromates on aluminum. Their data shows it is possible to meet the 168 hour salt spray requirement of MIL-C-5541, "Chemical Conversion Coating of Aluminum Alloys," without the use of chromium compounds. It may also be possible to use phosphate coatings in conjunction with other coatings on IVD aluminum to provide a corrosion protection system equal to the current chromate/paint systems. Another possible solution is the use of zirconate or titanate coupling agents as a surface treatment. All the above solutions would also serve as a base for paint adhesion.

3. Recommended R&D Program

MCAIR proposes to identify specific zirconium conversion coatings, phosphate coatings, and coupling agents and apply them to IVD aluminum-coated test specimens. Tests will be conducted to determine the following:

a. Corrosion resistance
b. Electrical conductivity
c. Paint adhesion
d. Service temperature
e. Resistance to common aircraft fluids
f. Environmental compliance

A flight evaluation is proposed for the best system as determined by laboratory tests. Cost Analysis will also be performed.

F. COST REDUCTION

1. Problem

In general, IVD aluminum has been shown to be a cost effective substitute for cadmium, see Section VIII. However, a dedicated cost reduction effort would have significant payoff. Such an effort is especially timely since IVD aluminum is in the early stages of growing acceptance and use by military overhaul facilities and major government contractors.

2. Proposed Solution

Analyze current operations to establish their contribution to total cost and their potential for improvement. A top-down approach should be followed which starts at the overhaul or coating facility level and is progressively broken down to the detailed processing steps for a select group of generic airframe or engine parts. Activities that are labor intensive, use critical materials, and involve extensive planning and control will receive high priority for modernization. From this analysis, an automated, fully integrated production cell will be designed and implemented. The cell will be flexible to changes in workload requirements and part configuration.

3. Recommended R&D Program

MCAIR proposes to select an ALC with a high level of current or potential IVD coating work and conduct a detailed top-down cost analysis. Production operations with a cost savings potential will be identified. A study will be made to select between either an improved manual operation or full automation. Changes will be implemented and compared with current operations as to their contribution to cost and/or quality. The final report will reflect total cost savings and serve as a guide for similar improvements to other ALC operations.

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